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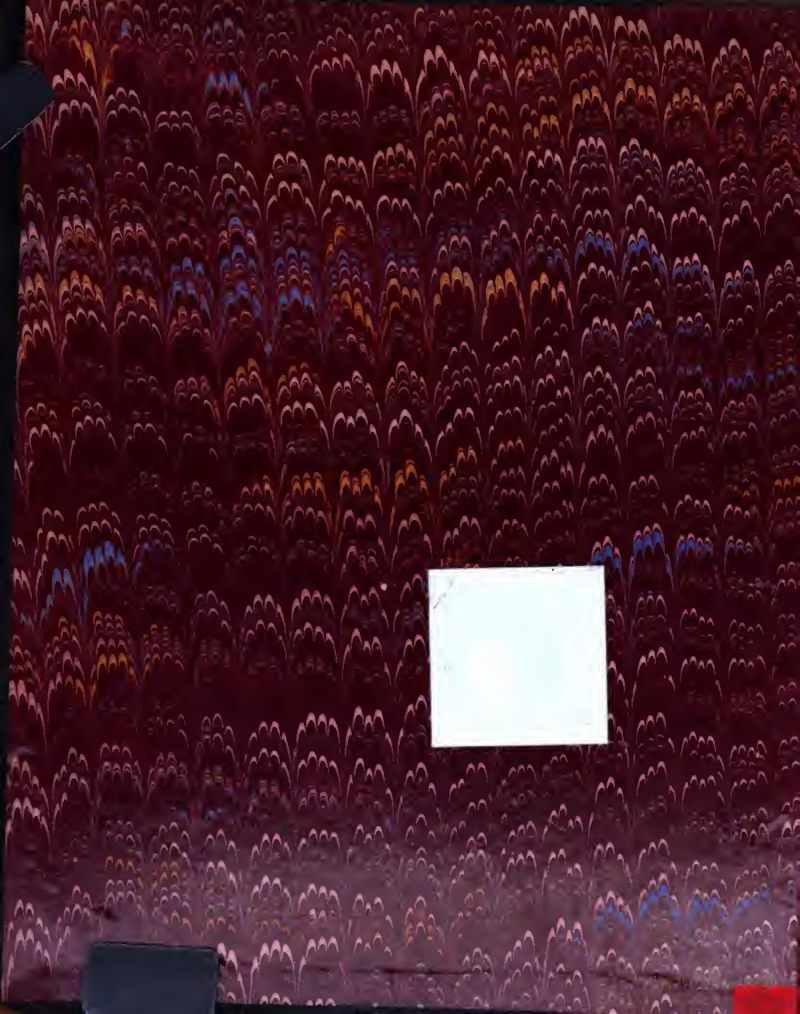

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ERRATA.

Page 54, line 7. For *collect-groups* read *generator-groups*.

" 106, § 31. The first formula should read $(A \pm B)\,C = AC \pm BC$.

" 126. The third formula should read $k(i-k)=j$.

" 132. Foot-note, second line of second paragraph, read $j=\frac{1}{2}(j_1-\mathrm{J}k_1)$, $l=\frac{1}{2}(1+\mathrm{J}i_1)$.

". 136. Last line of foot-note. For e, read l.

" 148. Multiplication table of (l_1). For $ji=i$, read $ji=j$.

" 171. Last line of foot-note, insert l, at beginning of line.

" 182. Foot-note. Add that on substituting $k+\mathrm{r}j$ for k, the algebra (ae_r) reduces to (ax_1), and the same substitution reduces (ay_r) to (ax_1).

" 187. Last line of foot-note. For i, read l.

" 246, line 14. After the word *that* insert *with a value of k capable of being made less than any assignable quantity.*

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On the 34 Concomitants of the Ternary Cubic.

By Professor Cayley, *Cambridge, England.*

I have (by aid of Gundelfinger's formulæ, afterwards referred to,) calculated, and I give in the present paper, the expressions of the 34 concomitants of the canonical ternary cubic $ax^3 + by^3 + cz^3 + 6lxyz$, or, what is the same thing, the 34 covariants of this cubic and the adjoint linear function $\xi x + \eta y + \zeta z$: this is the chief object of the paper. I prefix a list of memoirs, with short remarks upon some of them; and, after a few observations, proceed to the expressions for the 34 concomitants; and, in conclusion, exhibit the process of calculation of these concomitants other than such of them as are taken to be known forms. I insert a supplemental table of 6 derived forms.

The list of memoirs (not by any means a complete one) is as follows:

Hesse, Ueber die Elimination der Variabeln aus drei algebraischen Gleichungen vom zweiten Grade mit zwei Variabeln: *Crelle*, t. xxviii (1844), pp. 68–96. Although purporting to relate to a different subject, this is in fact the earliest, and a very important, memoir in regard to the general ternary cubic; and in it is established the canonical form, as Hesse writes it, $y_1^3 + y_2^3 + y_3^3 + 6\pi y_1 y_2 y_3$.

Aronhold, Zur Theorie der homogenen Functionen dritten Grades von drei Variabeln: *Crelle*, t. xxxix (1850), pp. 140–159.

Cayley, A Third Memoir on Quantics: *Phil. Trans.*, t. cxlvi (1856), pp. 627–647.

Aronhold, Theorie der homogenen Functionen dritten Grades von drei Variabeln: *Crelle*, t. lv (1858), pp. 97–191.

Salmon, Lessons Introductory to the Modern Higher Algebra: 8°, Dublin, 1859.

Cayley, A Seventh Memoir on Quantics: *Phil. Trans.*, t. cli (1861), pp. 277–292.

Brioschi, Sur la theorie des formes cubiques a trois indeterminées: *Comptes Rendus*, t. lvi (1863), pp. 304–307.

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HERMITE, Extrait d'une lettre à M. Brioschi: *Crelle*, t. lxiii (1864), pp. 30–32, followed by a note by BRIOSCHI, pp. 32–33.

The skew covariant of the ninth order $(y^3 - z^3 . z^3 - x^3 . x^3 - y^3$ for the canonical form $x^3 + y^3 + z^3 + 6lxyz)$, and the corresponding contravariant $\eta^3 - \zeta^3 . \zeta^3 - \xi^3 . \xi^3 - \eta^3$, alluded to p. 116 of Salmon's Lessons, were obtained, the covariant by Brioschi and the contravariant by Hermite, in the last-mentioned papers.

CLEBSCH and GORDAN, Ueber die Theorie der ternären cubischen Formen: *Math. Annalen*, t. i (1869), pp. 56–89.

The establishment of the complete system of the 34 covariants, contravariants and *Zwischenformen*, or, as I have here called them, the 34 concomitants, was first effected by Gordan in the next following memoir:

GORDAN, Ueber die ternären Formen dritten Grades: *Math. Annalen*, t. i (1869), pp. 90–128.

And the theory is further considered:

GUNDELFINGER, Zur Theorie der ternären cubischen Formen: *Math. Annalen* t. vi (1871), pp. 144–163. The author speaks of the 34 forms as being "theils mit den von Gordan gewählten identisch, theils möglichst einfache Combinationen derselben." They are, in fact, the 34 forms given in the present paper for the canonical form of the cubic, and the meaning of the adopted combinations of Gordan's forms will presently clearly appear.

There is an advantage in using the form $ax^3 + by^3 + cz^3 + 6lxyz$ rather than the Hessian form $x^3 + y^3 + z^3 + 6lxyz$, employed in my Third and Seventh Memoirs on Quantics: for the form $ax^3 + by^3 + cz^3 + 6lxyz$ is what the general cubic $(a, b, c, f, g, h, i, j, k, l)(x, y, z)^3$ becomes by no other change than the reduction to zero of certain of its coefficients; and thus any concomitant of the canonical form consists of terms which are leading terms of the same concomitant of the general form.

The concomitants are functions of the coefficients $(a, b, \ldots l)$, of (ξ, η, ζ), and of (x, y, z): the dimensions in regard to the three sets respectively may be distinguished as the degree, class, and order; and we have thus to consider the deg-class-order of a concomitant.

Two or more concomitants of the same deg-class-order may be linearly combined together: viz., the linear combination is the sum of the concomitants each multiplied by a mere number. The question thus arises as to the selection of a representative concomitant. As already mentioned, I follow Gundelfinger,

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viz., my 34 concomitants of the canonical form correspond each to each (with only the difference of a numerical factor of the entire concomitant) to his 34 concomitants of the general form. The principle underlying the selection would, in regard to the general form, have to be explained altogether differently; but this principle exhibits itself in a very remarkable manner in regard to the canonical form $ax^3 + by^3 + cz^3 + 6lxyz$.

Each concomitant of the general form is an indecomposable function, not breaking up into rational factors; but this is not of necessity the case in regard to a canonical form (only a concomitant which *does* break up must be regarded as indecomposable, no factor of such concomitant being rejected, or separated). So far from it, there is, in regard to the canonical form in question, a frequent occurrence of $abc + 8l^3$ or a power thereof, either as a factor of a unique concomitant, or when there are two or more concomitants of the same deg-class-order, then as a factor of a properly selected linear combination of such concomitants: and the principle referred to is in fact that of the selection of such combination for the representative concomitant; or (in other words) the representative concomitant is taken so as to contain as a factor the highest power that may be of $abc + 8l^3$. (As to the signification of this expression $abc + 8l^3$, I call to mind that the discriminant of the form is $abc(abc + 8l^3)^3$).

As to numerical factor: my principle has been, and is, to throw out any common numerical divisor of all the terms: thus I write $S = -abcl + l^4$, instead of Aronhold's $S = -4abcl + 4l^4$. There is also the question of nomenclature: I retain that of my Seventh Memoir on Quantics, except that I use single letters H, P, &c., instead of the same letters with U, thus HU, PU, &c.; in particular I use U, H, P, Q instead of Aronhold's f, Δ, S_f, T_f. It is thus at all events necessary to make some change in Gundelfinger's letters; and there is moreover a laxity in his use of accented letters; his B, B', B'', B''', and so in other cases E', E'', &c., are used to denote functions derived in a determinate manner each from the preceding one (by the δ-process explained further on); whereas his L, L'; M, M'; N, N' are functions having to each other an altogether different relation; also three of his functions are not denoted by any letters at all. Under the circumstances, I retain only a few of his letters; use the accent where it denotes the δ-process; and introduce barred letters $\overline{J}$, $\overline{K}$, &c., to denote a different correspondence with the unbarred letters J, K, &c. But I attach also to each concomitant a numerical symbol showing its deg-class-order, thus: 541 (degree = 5, class = 4, order = 1) or 1290, (there is no ambiguity in the two-digit numbers 10, 11, 12 which present themselves in the system

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of the 34 symbols): and it seems to me very desirable that the significations of these deg-class-order symbols should be considered as permanent and unalterable. Thus, in writing $S = 400 = -abcd + I^4$, I wish the 400 to be regarded as denoting its expressed value $-abcd + I^4$: if the same letter S is to be used in Aronhold's sense to denote $-4abcd + 4I^4$, this would be completely expressed by the new definition $S = \mathbf{4}.400$, the meaning of the symbol 400 being explained by reference to the present memoir, or by the actual quotation $400 = -abcd + I^4$.

I proceed at once to the table: for shortness, I omit in general terms which can be derived from an expressed term by mere cyclical interchanges of the letters (a, b, c), (ξ, η, ζ), (x, y, z).

Table of the 34 Covariants of the Canonical Cubic $ax^3 + by^3 + cz^3 + 6lxyz$ *and linear form* $\xi x + \eta y + \zeta z$.

First Part, 10 Forms. Class = Order.

Current No.		
1	$S = 400 =$	$-abcd + I^4.$
2	$T = 600 =$	$a^2b^2c^2 - 20abcd - 8I^4.$
3	$\Lambda = 011 =$	$\xi x + \eta y + \zeta z.$
4	$\Theta = 222 =$	$x^2\,[-I^2\xi^2 - 2al\eta\zeta]\,..$
		$+ yz\,[bc\xi^2 + 2I^2\eta\zeta]\,..$
5	$\Theta' = 422 =$	$x^2\,[\,l\,(abc + 2I^3)\,\xi^2 + a\,(abc - 4I^3)\,\eta\zeta]\,..$
		$+ yz\,[bcI^2\xi^2 - 2\,(abc + 2I^3)\,\eta\zeta]\,..$
6	$\Theta'' = 622 =$	$x^2\,[-(abc + 2I^3)^2\xi^2 + 12aI^2(abc + 2I^3)\,\eta\zeta]\,..$
		$+ yz\,[36bcI^2\xi^2 + 2\,(abc + 2I^3)^2\eta\zeta]\,..$
7	$B = 333 =$	$x^3\,[a^2\,(c\eta^3 - b\zeta^3)\,]\,..$
		$+ y^2z\,[(abc + 8I^3)\,\eta^2\zeta + 12bI^2\zeta^2\xi + 6bcI\xi^2\eta]\,..$
		$+ yz^2\,[-(abc + 8I^3)\,\eta\zeta^2 - 6bcI\zeta\xi^2 - 12cI^2\xi\eta^2]\,..$
8	$B' = 533 =$	$x^3\,[3a^2I^2\,(c\eta^3 - b\zeta^3)]\,..$
		$+ y^2z\,[-I^2\,(abc + 8I^3)\,\eta^2\zeta + 4bI\,(-abc + I^3)\,\zeta^2\xi$
		$\qquad - bc\,(abc - 10I^3)\,\xi^2\eta]\,..$
		$+ yz^2\,[I^2(abc + 8I^3)\,\eta\zeta^2 + bc\,(abc - 10I^3)\,\zeta\xi^2$
		$\qquad - 4cI\,(-abc + I^3)\,\xi\eta^2]\,..$
9	$B'' = 733 =$	$x^3\,[9a^2I^4\,(c\eta^3 - b\zeta^3)]\,..$
		$+ y^2z\,[I\,(abc + 8I^3)\,(2abc + I^3)\,\eta^2\zeta$
		$\qquad + b\,(abc + 2I^3)(abc - 10I^3)\,\zeta^2\xi + 6bcI^2(-abc + I^3)\,\xi^2\eta]\,..$
		$+ yz^2\,[-I\,(abc + 8I^3)(2abc + I^3)\,\eta\zeta^2$
		$\qquad - 6bcI^2(-abc + I^3)\,\zeta\xi^2 - c\,(abc + 2I^3)(abc - 10I^3)\,\xi\eta^2]\,..$

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Current No.

10 $$B'' = 933 = \begin{aligned} & x^3\,[27a^2l^6\,(cy^3 - bz^3)]\,. \\ & + y^3z\,[-\,(abc + 8l^3)(abc - l^3)^3x^3\zeta + 9bl^3\,(abc + 2l^3)^2\eta^3\xi \\ & \qquad - 27bcl^6\,(abc + 2l^3)\,\xi^3x] \,. \\ & + yz^3\,[(abc + 8l^3)(abc - l^3)^3x\eta^3 + 27bcl^6\,(abc + 2l^3)\,\zeta\xi^3 \\ & \qquad - 9cl^3\,(abc + 2l^3)^2\xi\eta^3] \,. \end{aligned}$$

Second Part, (4 + 4 =) 8 forms. Class = 0, and Order = 0.

Class = 0.

11 $$U = 103 = ax^3 + by^3 + cz^3 + 6lxyz.$$

12 $$H = 303 = l^3\,(ax^3 + by^3 + cz^3) - (abc + 2l^3)\,xyz.$$

13 $$\Psi = 806 = (abc + 8l^3)^2\{a^2x^6 + b^2y^6 + c^2z^6 - 10\,(bcy^2z^2 + cax^2x^2 + abx^2y^2)\}.$$

14 $$\Omega = 1209 = (abc + 8l^3)^3\{by^3 - cz^3.cz^3 - ax^3.ax^3 - by^3\}.$$

Order = 0.

15 $$P = 330 = -\,l\,(bc\xi^3 + cay^3 + abz^3) + (-\,abc + 4l^3)\,\xi\eta\zeta.$$

16 $$Q = 530 = (abc - 10l^3)(bc\xi^3 + cay^3 + abz^3) - 6l^3\,(5abc + 4l^3)\,\xi\eta\zeta.$$

17 $$\begin{aligned} F = 460 = {} & b^2c^2\xi^6 + c^2a^2\eta^6 + a^2b^2\zeta^6 - 2\,(abc + 16l^3)(a\eta^3\zeta^3 + b\zeta^3\xi^3 + c\xi^3\eta^3) \\ & - 24l^3\,(bc\xi^3 + ca\eta^3 + ab\zeta^3)\,\xi\eta\zeta - 24l\,(abc + 2l^3)\,\xi^3\eta^3\zeta^3. \end{aligned}$$

18 $$\Pi = 1290 = (abc + 8l^3)^3\{cy^3 - bz^3.az^3 - c\xi^3.b\xi^3 - ax^3\}.$$

Third Part, (8 + 8 =) 16 forms. Class less or greater than Order.

Class less than Order.

19 $$J = 414 = (abc + 8l^3)\{\xi x(by^3 - cz^3) + \eta y\,(cz^3 - ax^3) + \zeta z\,(ax^3 - by^3)\}.$$

20 $$K = 514 = (abc + 8l^3)\{\xi\,[alx^4 - 2blxy^3 - 2clxz^3 + 3bcy^2z^2]\,..\{.$$

21 $$\begin{aligned} K' = 714 = {} & (abc + 8l^3)\{\xi\,[(abc + 2l^3)\,(ax^4 - 2blxy^3 - 2clxz^3) \\ & \qquad - 18bcl^2y^2z^2]\,..\{. \end{aligned}$$

22 $$\begin{aligned} E = 625 = {} & (abc + 8l^3)\,\}\xi^2\,(by^3 - cz^3)\,[2l^2x^3 + bcyz]\,.. \\ & + \eta\zeta\,(by^3 - cz^3)[4alx^3 + 2l^2yz]\,..\{. \end{aligned}$$

23 $$\begin{aligned} E' = 825 = {} & (abc + 8l^3)\,\}\xi^2\,(by^3 - cz^3)[l\,(abc + 2l^3)\,x^3 - 3bcl^2yz]\,.. \\ & + \eta\zeta\,(by^3 - cz^3)[\,a\,(abc - 4l^3)\,x^3 + l\,(abc + 2l^3)\,yz]\,..\{. \end{aligned}$$

24 $$\begin{aligned} E'' = 1025 = {} & (abc + 8l^3)\,\}\xi^2\,(by^3 - cz^3)[(abc + 2l^3)^2\,x^3 + 18bcl^3yz]\,.. \\ & + \eta\zeta(by^3 - cz^3)[-12al^2(abc + 2l^3)\,x^3 + (abc + 2l^3)^2yz]\,..\{. \end{aligned}$$

25 $$M = 917 = (abc + 8l^3)^2\,\}\xi\,(by^3 - cz^3)[5alx^4 - blxy^3 - clxz^3 - 3bcy^2z^2]\,..\{.$$

26 $$\begin{aligned} M' = 1117 = {} & (abc + 8l^3)^3\,\}\xi\,(by^3 - cz^3)[(abc + 2l^3)(5alx^4 - lxy^3 - cxz^3) \\ & \qquad + 18bcl^2y^2z^2]\,..\{. \end{aligned}$$

Order less than Class.

27 $$\bar{J} = 841 = (abc + 8l^3)^2\,\}x\xi a\,(cy^3 - bz^3) + y\eta b(az^3 - c\xi^3) + z\zeta c\,(b\xi^3 - ay^3)\}.$$

28 $$\bar{K} = 541 = (abc + 8l^3)\,\}\,x\,[bc\xi^4 - 2ca\xi y^3 - 2ab\xi\zeta^3 - 6abl\eta^3\zeta^3]\,..\{.$$

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Current No. Order less than Class.

29 $K' = 741 = (abc+8P)\{x[P(bc\xi^2-2cx\xi x^2-2abx\xi\zeta^2)+a(abc+2P)x^2\zeta^2]\ldots\}$.

30 $E = 652 = (abc+8P)\{x^3\ (cx^3-b\zeta^3)[2a\xi^3+a^2x\zeta]\ \ldots$
$+ yz\ (cx^3-b\zeta^3)[4P\xi^3+2abx\zeta]\ \ldots\}$.

31 $E' = 852 = (abc+8P)\{x^3\ (cx^3-b\zeta^3)\ [a\ (abc-4P)\ \xi^3-6a^2P\ x\zeta]\ \ldots$
$+ yz\ (cx^3-b\zeta^3)[4I\ (abc+2P)\ \xi^3+a\ (abc-4P)\ x\zeta]\ \ldots\}$.

32 $E'' = 1052 = (abc+8P)\{x^3\ (cx^3-b\zeta^3)\ [-3aP\ (abc+2P)\ \xi^3+9a^2P\ x\zeta]\ \ldots$
$+ yz\ (cx^3-b\zeta^3)[(abc+2P)^2\xi^3-3aP(abc-4P)\ x\zeta]\ \ldots\}$.

33 $M = 771 = (abc+8P)\{x\ (cx^3-b\zeta^3)\ [(abc-8P)\ \xi^4-a^2c\xi x^3-a^2b\xi\zeta^3$
$-12aP\xi^2x\zeta-6a^2bx^2\zeta^2]\ \ldots\}$.

34 $M' = 971 = (abc+8P)\{x(cx^3-b\zeta^3)[P(7abc+8P)\xi^4-3a^2cP\xi x^3-3a^2bP\xi\zeta^3$
$+4aI\ (abc-P)\ \xi^2x\zeta+a^3\ (abc-10P)\ x^2\zeta^2]\ \ldots\}$.

To this may be joined the following Supplemental Table of certain Derived Forms:

35 $R = 1200 = 64S^3-T^2 = -abc\ (abc+8P)^3$.

36 $C = 703 = -TU+24SH = (abc+8P)\{(-abc+4P)(ax^2+by^2+cz^2)$
$+18abcIxyz\}$.

37 $D = 903 = 8S^2U-3TH = (abc+8P)\{P(5abc+4P)(ax^2+by^2+cz^2)$
$+3abc\ (abc-10P)\ xyz\}$.

38 $Y = 930 = 3TP-4SQ = (abc+8P)^3\{I\ (bc\xi^2+cax^2+ab\zeta^2)$
$-3abc\xi x\zeta\}$.

39 $Z = 1130 = -48S^2P+TQ = (abc+8P)^2\{(abc+2P)(bc\xi^2+cax^2+ab\zeta^2)$
$+18abcP\xi x\zeta\}$.

40 $\Phi = 1640 = 12\ (abc+8P)^3F-288STH^2+768S^2PQ-8TQ^2$
$= (abc+8P)^2\{b^2c^2\xi^2+c^2a^2x^2+a^2b^2\zeta^2$
$-10abc\ (cx^2\zeta^2+b\zeta^2\xi^2+c\xi^2x^2)\}$.

viz., these are derived forms characterized by having a power of $abc+8P$ as a factor: R is the discriminant; C, D, Y, Z occur in Aronhold, and see my Seventh memoir on Quantics: Φ in Clebsch and Gordan's memoir of 1869.

I regard as known forms A, U, H, P, Q, S, T, F, that is, the eight forms 3, 11, 12, 15, 16, 1, 2, 17; the remaining 26 forms are expressed in terms of these by formulæ involving notations which will be explained, viz: We have

13 $\Psi = 3\ (bc'+b'c-2ff', \ldots gh'+g'h-af'-a'f, \ldots)(X, Y, Z)(X', Y', Z') + TU^2$.

14 $\Omega = \frac{1}{18}$ Jac (U, H, Ψ).

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18 $\Pi = -\frac{1}{36}[\mathrm{Jac}](P, Q, F)$.
4 $\Theta = (\mathrm{bc} - \mathrm{f}^2, \ldots \mathrm{gh} - \mathrm{af}, \ldots)(\xi, \eta, \zeta)^2$.
5 $\Theta' = \frac{1}{2}\delta\Theta$.
6 $\Theta' = \frac{1}{2}\delta^2\Theta$.
7 $B = -\frac{1}{2}\mathrm{Jac}(U, \Theta, \Lambda)$.
8 $B' = \frac{1}{6}\delta B$.
9 $B'' = \frac{1}{24}\delta^2 B$.
10 $B''' = \frac{1}{60}\delta^3 B$.
19 $J = -\frac{1}{2}\mathrm{Jac}(U, H, \Lambda)$.
27 $\bar{J} = -\frac{1}{6}[\mathrm{Jac}](P, Q, \Lambda)$.
20 $K = -\frac{3}{2}\{\partial_t\Theta\partial_{xyz}H + \partial_x\Theta\partial_{yzt}H + \partial_y\Theta\partial_{ztx}H + \partial_z\Theta\partial_{txy}H\} - SU\Lambda$.
21 $K' = -(\delta)K$.
28 $\bar{K} = 3\{\partial_x\Theta\partial_{yzt}P + \partial_y\Theta\partial_{ztx}P + \partial_z\Theta\partial_{txy}P\} + Q\Lambda$.
29 $\bar{K}' = \frac{1}{6}(\delta)\bar{K}$.
22 $E = -\frac{1}{16}\mathrm{Jac}(K, U, \Lambda)$.
23 $E' = -\frac{1}{4}(\delta)E$.
24 $E'' = \frac{1}{4}(\delta^2)E$.
30 $\bar{E} = -\frac{1}{8}\mathrm{Jac}(\bar{K}, U, \Lambda)$.
31 $\bar{E}' = -\frac{1}{8}(\delta)\bar{E}$.
32 $\bar{E}'' = -\frac{1}{8}(\delta^2)E$.
25 $M = \frac{1}{36}\mathrm{Jac}(U, \Psi, \Lambda)$.
26 $M' = -(\delta)M$.
33 $\bar{M} = -\frac{1}{6}[\mathrm{Jac}](P, F, \Lambda)$.
34 $\bar{M}' = \frac{1}{6}(\delta)M$.

In explanation of the notations, observe that

$$U = ax^3 + by^3 + cz^3 + 6lxyz,$$
$$H = l^2(ax^3 + by^3 + cz^3) - (abc + 2l^3)xyz.$$

Hence, writing

$$6H = a'x^3 + b'y^3 + c'z^3 + 6l'xyz,$$

we have

$$a', b', c', l' = 6al^2, 6bl^2, 6cl^2, -(abc + 2l^3).$$

And this being so, we write

$$X, Y, Z = ax^2 + 2lyz, by^2 + 2lzx, cz^2 + 2lxy,$$
$$\mathrm{a}, \mathrm{b}, \mathrm{c}, \mathrm{f}, \mathrm{g}, \mathrm{h} = ax, by, cz, lx, ly, lz,$$

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for $\frac{1}{3}$ of the first differential coefficients, and $\frac{1}{6}$ of the second differential coefficients of U; and in like manner

$$X', Y', Z' = af^2 + 2f'yz, \quad bg^2 + 2f'zx, \quad ch^2 + 2f'xy,$$
$$a', b', c', f', g', h' = a'x, b'y, c'z, f'x, f'y, f'z,$$

for $\frac{1}{3}$ of the first differential coefficients, and $\frac{1}{6}$ of the second differential coefficients of $6H$.

Jac. is written to denote the Jacobian, viz:

$$\mathrm{Jac}\,(U, H, \Theta) = \begin{vmatrix} \partial_x U, & \partial_y U, & \partial_z U \\ \partial_x H, & \partial_y H, & \partial_z H \\ \partial_x \Theta, & \partial_y \Theta, & \partial_z \Theta \end{vmatrix},$$

and in like manner [Jac] to denote the Jacobian, when the differentiations are in regard to (ξ, η, ζ) instead of (x, y, z): δ is the symbol of the Δ-process, or substitution of the coefficients (a', b', c', f') in place of (a, b, c, f): in fact $\Delta = a'\partial_a + b'\partial_b + c'\partial_c + f'\partial_f$: Δ, Δ^2, &c.. each operate directly on a function of (a, b, c, f), the (a', b', c', f') of the symbol δ being in the first instance regarded as constants, and being replaced ultimately by their values; for instance, $\Delta abc = a'bc + ab'c + abc'$, $\Delta^2 abc = 2(ab'c' + a'bc' + a'b'c)$, $\delta^2 abc = 6a'b'c'$.

In several of the formulæ, instead of δ or δ^2, the symbol used is (δ) or (δ^2): in these cases the function operated upon contains the factor $(abc + \delta f')$ or $(abc + \delta f')^2$, and is of the form $(abc + \delta f')(aU + bV + cW)$ or $(abc + \delta f')^2 (a^2U + ab\,V + \&c.)$: the meaning is, that the δ or δ^2 is supposed to operate through the $(abc + \delta f')a$, or $(abc + \delta f')^2 a^2$, &c.. as if this were a constant, upon the U, V, &c.. only; thus: $(\delta).(abc + \delta f')(aU + bV + cW)$ is used to denote $(abc + \delta f')(a\delta U + b\delta V + c\delta W)$. As to this, observe that, operating with δ instead of (δ), there would be the additional terms $U\delta(abc + \delta f')a$ &c.; we have in this case $\delta(abc + \delta f')a$, $= a(2a'bc + ab'c + abc' + 24f'f) + 8f'a'$, $= 24a^2bcf - 24a^2(abc + 2f') + 48af'$, $= 0$; or the rejected terms in fact vanish. For $(\delta^2).(abc + \delta f')(aU + bV + cW)$, operating with δ^2, we should have, in like manner, terms $U\delta^2(abc + \delta f')a$, &c.; here $\delta^2(abc + \delta f')a = a^2bc + 2aba'c' + 2aca'b' + a^2b'c' + 24f'a'f' + 24af'^2$, which is found to be $= -24a(abc + \delta f') (= abcf - f^4)$, that is, $= -24S(abc + \delta f')a$; and the terms in question are thus $= -24S(abc + \delta f')(aU + bV + cW)$, viz. $(abc + \delta f')(aU + bV + cW)$ being a covariant, this is also a covariant; that is, in using (δ^2) instead of δ^2, we in fact reject certain covariant terms; or say, for instance, $\delta^2 E$ being a covariant, then $(\delta^2)E$ is also a covariant, but a different covariant. The calculation with (δ)

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or (δ^2) is more simple than it would have been with δ or δ^2. See *post*, the calculations of K', $\overline{K}'$, &c.

I give for each of the 26 covariants a calculation showing how at least a single term of the final result is arrived at, and, in the several cases for which there is a power of $abc + 8l^3$ as a factor, showing how this factor presents itself.

Calculations for the 26 Covariants.

13. $\Psi = 3\,(bc' + b'c - 2ff', \ldots gh' + g'h - af' - a'f, \ldots)[X, Y, Z][X', Y', Z') + TU^2,$
$= 3\,((bc' + b'c)yz - 2(lf' + l'f)x^2, \ldots)[ax^2 + 2fyz, \ldots)(a'x^2 + 2f'yz, \ldots)$
$+ T(a^2x^2 + \ldots).$

The whole coefficient of x^4 is
$$-6ll'aa' + Ta^2, \quad = 36a^2l^2\,(abc + 2l^3) + Ta^2,$$
viz. the coefficient of a^2x^4 is
$$= 36l^3\,(abc + 2l^3) + a^2b^2c^2 - 20abcl^3 - 8l^6$$
$$= a^2b^2c^2 + 16abcl^3 + 64l^6,$$
$$= (abc + 8l^3)^2.$$

14. $$\Omega = \tfrac{1}{18}\,\mathrm{Jac}\,(U, H, \Psi), = \tfrac{1}{2}\begin{vmatrix} X, & X', & \frac{1}{a}\partial_x\Psi \\ Y, & Y', & \frac{1}{b}\partial_y\Psi \\ Z, & Z', & \frac{1}{c}\partial_z\Psi \end{vmatrix}.$$

Here
$$YZ' - Y'Z = (by^2 + 2lzx)(c'z^2 + 2l'xy) - (cz^2 + 2lxy)(b'z^2 + 2l'xy),$$
$$= (bc' - b'c)\,y^2z^2 + (2\,bl' - b'l)\,xy^2 - 2\,(cl' - c'l)\,xz^2,$$
$$= -2\,(abc + 8l^3)\,x\,(by^2 - cz^2);$$
$$\tfrac{1}{2}\cdot\tfrac{1}{c}\,\partial_z\Psi = \tfrac{1}{2}\,(a^2x^2 - 5abx^2y^2 - 5acx^2z^2).$$

Hence the whole is
$$= -(abc + 8l^3)\{l^2x^2\,(by^2 - cz^2) + b^2y^2\,(cz^2 - ax^2) + c^2z^2\,(ax^2 - by^2)\},$$
$$= (abc + 8l^3)(by^2 - cz^2)(cz^2 - ax^2)(ax^2 - by^2).$$

18. $$\Pi = -\tfrac{1}{36}\,[\mathrm{Jac}](P, Q, F) = -\tfrac{1}{36}\begin{vmatrix} \partial_\xi P, & \partial_\xi Q, & \partial_\xi F \\ \partial_\eta P, & \partial_\eta Q, & \partial_\eta F \\ \partial_\zeta P, & \partial_\zeta Q, & \partial_\zeta F \end{vmatrix},$$

viz. if, in this calculation, we write
$$6P = a\xi^3 + b\eta^3 + c\zeta^3 + 6l\xi\eta\zeta, \text{ i. e. } a, b, c, l = -6bc, \ -6ca, \ -6ab, \ -abc + 4l^3$$
$$Q = a'\xi^3 + b'\eta^3 + c'\zeta^3 + 6l'\xi\eta\zeta, \quad ,, \quad a', b', c', l' = (abc - 10l^3)(bc, \ ca, \ ab), \ -l\,(5abc + 4l^3),$$
then
$$\Pi = -\tfrac{1}{4}\begin{vmatrix} a\xi^2 + 2\,l\eta\zeta, & a'\xi^2 + 2\,l'\eta\zeta, & \frac{1}{a}\partial_\xi F \\ b\eta^2 + 2\,l\zeta\xi, & b'\eta^2 + 2\,l'\zeta\xi, & \frac{1}{b}\partial_\eta F \\ c\zeta^2 + 2\,l\xi\eta, & c'\zeta^2 + 2\,l'\xi\eta, & \frac{1}{c}\partial_\zeta F \end{vmatrix}.$$

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Here

$$(b\eta^2 + 2l\zeta\xi)(c\xi^2 + 2l'\xi\eta) - (l'\eta^2 + 2l'\zeta\xi)(c\xi^2 + 2l\zeta\xi)$$
$$= (bc' - b'c)\,\eta^2\zeta^2 + 2\,(bl' - b'l)\,\xi\eta^2 - 2\,(cl' - c'l)\,\xi^2\zeta,$$

or since

$$bc' - b'c = 0,$$
$$bl' - b'l = -6lc\alpha, \quad -l^2\,(5abc + 4l^3) - (abc - 10l^3)\,c\alpha\,(-abc + 4l^3)$$
$$= c\alpha\,\{6l^2\,(5abc + 4l^3) + (abc - 4l^3)(abc - 10l^3)\}$$
$$= c\alpha\,(abc + 8l^3)^2,$$

and the like for $cl' - c'l$, the expression is

$$= 2\,(abc + 8l^3)^2(c\alpha\eta^3 - ab\zeta^2)\,\xi;$$

and the whole is thus

$$= -\tfrac{1}{2}\,(abc + 8l^3)^2\{(c\alpha\eta^3 - ab\zeta^2)\,\xi\,.\,\tfrac{1}{4}\,\partial_l F + \ldots\}$$
$$= -\tfrac{1}{2}\,(abc + 8l^3)^2\{(c\alpha\eta^3 - ab\zeta^2)[b^2c^2\xi^4 - (abc + 16l^3)(b\zeta^2\xi^2 + c\xi^3\eta^2) + \&c.]$$
$$+ (ab\zeta^2 - bc\xi^2)[c^2a^2\eta^4 - (abc + 16l^3)(c\xi^2\eta^2 + a\eta^2\zeta^2) + \&c.]$$
$$+ (bc\xi^3 - ca\eta^2)[a^2b^2\zeta^4 - (abc + 16l^3)(a\eta^2\zeta^2 + b\zeta^2\xi^2) + \&c.]\}.$$

Here the coefficient of $\xi^2\eta^2$, inside the $\{\}$, is

$$ab^2c^2 + bc^2\,(abc + 16l^3), = 2bc^2\,(abc + 8l^3),$$

and consequently the whole is

$$= -\,(abc + 8l^3)^2(bc^2\xi^2\eta^2 - \ldots),$$
$$= \quad (abc + 8l^3)^2\{(c\eta^2 - b\zeta^2)(a\zeta^2 - c\xi^2)(b\xi^2 - a\eta^2)\}.$$

4. $$\Theta = \quad (\mathrm{bc} - \mathrm{f}^2, \ldots \mathrm{gh} - \mathrm{af}, \ldots)\xi, \eta, \zeta)^3$$
$$= \quad (bcyz - l^2x^2)\xi^3 \ldots + 2\,(l^2yz - alx^2)\eta\zeta \ldots$$

which are the terms of the final result

$$\Theta = x^2\,[-l^2\xi^3 - 2alx\zeta] + yz\,[bc\xi^3 + 2l^2\eta\zeta].$$

5 and 6. The δ-process applied to the terms of Θ just written down gives

$$\Theta' = \tfrac{1}{3}\,\delta\Theta = x^2\,[ll'\xi^2 - (al' + a'l)\,\eta\zeta] + yz\,[\tfrac{1}{3}(b\eta' + b'c)\,\xi^2 + 2ll'\eta\zeta],$$
$$\Theta'' = \tfrac{1}{2}\,\delta^2\Theta = x^2\,[-l^2\xi^2 - 2a'l'\eta\zeta] + yz\,[b'c'\xi^2 + 2l^2\eta\zeta],$$

and substituting for a', b', c', l' their values, we have the corresponding terms of Θ' and Θ'' respectively.

7. $$B = -\tfrac{1}{2}\,\mathrm{Jac.}(U, \Theta, \Lambda), = -\begin{vmatrix} X, & \partial_x\Theta, & \xi \\ Y, & \partial_y\Theta, & \eta \\ Z, & \partial_z\Theta, & \zeta \end{vmatrix}.$$

A term is $X(x\partial_x\Theta - \zeta\partial_y\Theta)$, and if, in this calculation, we write $\Theta = (A, B, C, F, G, H)(x, y, z)^3$, *i.e.* $A = -l^2\xi^3 - 2alx\zeta$, $\ldots F = \frac{1}{2}\,bc\xi^2 + l^2\eta\zeta$, then the term is

$$= (ax^2 + 2hyz)x.2(Gx - H\zeta) + y.2(Fx - B\zeta) + z.2(Cx - F\zeta)\}.$$

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Here

$$2(G\eta - H\zeta) = \eta(c\alpha\gamma^2 + l^2\zeta\xi) - \zeta(ab\zeta^2 + l^2\xi\gamma), = a(c\eta^3 - b\zeta^3),$$

and hence the whole term in x^3 is $= a^2x^3(c\eta^3 - b\zeta^3)$.

8, 9, 10. The coefficient of $x^3\eta^3$ in B is a^2c, and hence in δB, $\delta^2 B$, $\delta^3 B$ the coefficients of this term are $2a'ac + a^2c'$, $2a''c + 4aa'c'$, $6a'''c'$, whence in B', B'', $B''' = \frac{1}{6}\delta B, \frac{1}{24}\delta^2 B, \frac{1}{60}\delta^3 B$ respectively, the coefficients are

$$\begin{array}{lll} \frac{1}{6}(a^2c' + 2aa'c), & \frac{1}{12}(a''c + 2aa'c'), & \frac{1}{6}a'''c', \\ = 3l^2a^2c, & 9l^4a^2c, & 27l^6a^2c \text{ respectively.} \end{array}$$

19. $$J = -\frac{1}{3}\operatorname{Jac}(U, H, \Lambda) = -\frac{1}{2}\begin{vmatrix} X, & X', & \xi \\ Y, & Y', & \eta \\ Z, & Z', & \zeta \end{vmatrix};$$

a term is $-\frac{1}{2}(YZ' - Y'Z)\xi$, where, as in a previous calculation,

$$YZ' - Y'Z = -2(abc + 8l^3)x(by^3 - cz^3).$$

Hence, whole is

$$= (abc + 8l^3)\{\xi x(by^3 - cz^3) + \eta y(cz^3 - ax^3) + \zeta z(ax^3 - by^3)\}.$$

27. $$\bar{J} = \frac{1}{3}[\mathrm{Jac}](P, Q, \Lambda) = \frac{1}{3}\begin{vmatrix} a\xi^3 + 2l\eta\zeta, & a'\xi^3 + 2l'\eta\zeta, & x \\ b\eta^3 + 2l\zeta\xi, & b'\eta^3 + 2l'\zeta\xi, & y \\ c\zeta^3 + 2l\xi\eta, & c'\zeta^3 + 2l'\xi\eta, & z \end{vmatrix},$$

if, as in a previous calculation

$$6P = a\xi^3 + b\eta^3 + c\zeta^3 + 6l\xi\eta\zeta, \quad Q = a'\xi^3 + b'\eta^3 + c'\zeta^3 + 6l'\xi\eta\zeta.$$

Here, as before,

$$(b\eta^3 + 2l\zeta\xi)(c'\zeta^3 + 2l'\xi\eta) - (b'\eta^3 + 2l'\zeta\xi)(c\zeta^3 + 2l\xi\eta) = 2(abc + 8l^3)^2(c\alpha\eta^3 - ab\zeta^3)\xi.$$

Hence, whole is

$$= (abc + 8l^3)^2\{x\xi a(c\eta^3 - b\zeta^3) + y\eta b(a\zeta^3 - c\xi^3) + z\zeta c(b\xi^3 - a\eta^3)\}.$$

20. $$K = -\frac{3}{2}(\partial_\xi\Theta\partial_x H + \partial_\eta\Theta\partial_y H + \partial_\zeta\Theta\partial_z H) - SU\Lambda,$$

which, H being

$$= \frac{1}{6}(a'x^3 + b'y^3 + c'z^3 + 6l'xyz),$$

and putting $\Theta = (A, B, C, F, G, H\{\xi, \eta, \zeta)^2$, $A = -l^2x^2 + bcyz, \ldots$ $F = -alx^2 + l^2yz, \ldots$ is

$$\begin{aligned} = -\frac{3}{2}\{&(a'x^3 + 2l'yz)(A\xi + H\eta + G\zeta) \\ &+ (b'y^3 + 2l'zx)(H\xi + B\eta + F\zeta) \\ &+ (c'z^3 + 2l'xy)(G\xi + F\eta + C\zeta)\}. \end{aligned} \qquad -(-abcl + l^4)U(\xi x + \eta y + \zeta z)$$

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The whole coefficient of ξ is thus

$$= -\tfrac{3}{4}\{(a'x^2 + 2f'yz)\,A + (b'y^2 + 2f'zx)\,H + (c'z^2 + 2f'xy)\,G\} - (-abcd + f^2)Ux$$
$$= -\tfrac{1}{4}\{(a'x^2 + 2f'yz)(-f^2x^2 + bcyz) + (b'y^2 + 2f'zx)(-cd^2 + f^2xy)$$
$$+ (c'z^2 + 2f'xy)(-bd^2y^2 + f^2zx)\} - (-abcd + f^4)ax^4 + bcy^2 + ccz^2 + 6df^2yz\},$$

and herein the coefficient of x^4 is

$$= \tfrac{3}{4}a'f^2 - af(-abc + f^2). \quad = 9af^2 - af(-abc + f^2). \quad = (abc + 8f^3)af;$$

viz. we have thus the term $(abc + 8f^3)\xi . afx^4$ of the final result.

21. $K'' = -(\lambda)K$, where K is of the form $(abc + 8f^3)(aU + bV + cW)$, and operating with (λ), we obtain $(abc + 8f^3)(ab'U + bb'V + cb'W)$. Taking for instance the term of K, $(abc + 8f^3)\xi\,[afx^4 - 2bdxy^3 - 2cdxz^3 + 3bcy^2z^2]$, then, in operating with (λ), the term bc may be considered indifferently as belonging to bV or cW, and the resulting term of K' is

$$K' = -(\lambda)K = -(abc + 8f^3)\xi\,[af^2x^4 - 2bf'xy^3 - 2cf'xz^3 + 3bc'y^2z^2].$$
$$= (abc + 8f^3)\xi\,[(abc + 2f^3)ax^4 - 2bdxy^3 - 2cdxz^3) - 18bcf^3y^2z^2]$$

28. $K = 3\{\partial_x\Theta\partial_x P + \partial_y\Theta\partial_y P + \partial_z\Theta\partial_z P\} + QA$; viz. writing $\Theta = (A, B, C, F, G, H\,|\,x, y, z)^2$. $A = -f^2\xi^2 - 2adx\zeta \ldots F = \tfrac{1}{2}bc\xi^2 + f^2x\zeta, \ldots$ then this is

$$= 3\{[-3bcd\xi^2 + (-abc + 4f^3)x\zeta]\,2(Ax + Hy + Gz)$$
$$+ [-3cdy^2 + (-abc + 4f^3)\zeta\xi]\,2(Hx + By + Fz)$$
$$+ [-3abd\zeta^2 + (-abc + 4f^3)\xi x]\,2(Gx + Fy + Cz)\}$$
$$+ \{(abc - 10f^3)(bc\xi^2 + cdx^2 + ady^2) - 6f^2(5abc + 4f^3)\xi x\zeta\}(\xi x + xy + \zeta z).$$

The whole coefficient of x is thus

$$= 3\{[-3bcd\xi^2 + (-abc + 4f^3)x\zeta]\,(-2f^2\xi^2 - 4adx\zeta)$$
$$+ [-3cdy^2 + (-abc + 4f^3)\zeta\xi](adx^2 + f^2\xi x)$$
$$+ [-3abd\zeta^2 + (-abc + 4f^3)\xi x](acy^2 + f^2\zeta\xi)\}$$
$$+ \{(abc - 10f^3)(bc\xi^2 + cdx^2y^2 + adx\zeta^2) - 6f^2(5abc + 4f^3)\xi^2x\zeta\},$$

and herein the coefficient of ξ^4 is $18bcf^3 + (abc - 10f^3)bc$, $= (abc + 8f^3)bc$, giving, in the final result, the term $(abc + 8f^3)\xi . bcx^4$.

29. $$\overline{K}' = \tfrac{1}{6}(\delta)\overline{K}.$$

Here $\overline{K}$ is of the form $(abc + 8f^3)(aU + bV + cW)$, and we have

$$K' = \tfrac{1}{6}(abc + 8f^3)(ab'U + bb'V + cb'W).$$

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A term of $aU + bV + cW$ is $x\,[bc\xi^4 - 2ca\xi\eta^3 - 2ab\xi\zeta^3 - 6al\eta^3\zeta^3]$ where $bc\xi^4$ may be considered as belonging indifferently to bV or cW, and so for the other terms. The resulting term in $\frac{1}{6}\,(a\delta U + b\delta V + c\delta W)$ is thus

$$\tfrac{1}{6}\,x\,[bc'\xi^4 - 2ca'\xi\eta^3 - 2ab'\xi\zeta^3 - 6al'\eta^3\zeta^3],$$

which is $= x\,[l^3\,(bc\xi^4 - 2ca\xi\eta^3 - 2ab\xi\zeta^3) + a\,(abc + 2l^3)\,\eta^3\zeta^3]$, and we have thus a term of $\overline{K}'$.

22. $$E = -\tfrac{1}{18}\,\mathrm{Jac}\,(K,\ U,\ \Lambda):$$

K contains the factor $abc + 8l^3$, and if, omitting this factor, the value of K is called $A\xi + B\eta + C\zeta$, then we have

$$E = -\tfrac{1}{6}\,\{(\xi\partial_x A + \eta\partial_x B + \zeta\partial_x C)(Y\zeta - Z\eta) + (\xi\partial_y A + \eta\partial_y B + \zeta\partial_y C)(Z\xi - X\zeta) + (\xi\partial_z A + \eta\partial_z B + \zeta\partial_z C)\,(X\eta - Y\xi)\},$$

and the term herein in ξ^3 is $-\frac{1}{6}\,\xi^3\,(Z\partial_y A - Y\partial_z A)$, where A is

$$= alx^4 - 2blxy^3 - 2clxz^3 + 3bcy^3z^3;\ \text{viz. the coefficient of } \xi^3 \text{ is}$$

$$\begin{aligned} &= -\tfrac{1}{6}\,\{(cz^3 + 2lxy)\,(-6blxy^3 + 6bcyz^3) - (by^3 + 2lzx)\,(-6clxz^3 + 6bcy^3z)\},\\ &= \quad l^2cy^4z - bc^2yz^4 + 2bl^2x^2y^3 - 2cl^2x^3z^3,\\ &= \quad (2l^2x^3 + bcyz)\,(by^3 - cz^3): \end{aligned}$$

Hence, restoring the omitted factor $(abc + 8l^3)$, we have in E the term

$$(abc + 8l^3)\,\xi^3\,(by^3 - cz^3)\,[2l^2x^3 + bcyz].$$

23, 24. $$E' = -\tfrac{1}{4}\,(\delta)\,E; \quad E'' = \tfrac{1}{4}\,(\delta^2)\,E:$$

E is of the form $(abc + 8l^3)\,(aU + bV + cW)$, and, as before, in a term such as $(abc + 8l^3)\,\xi^3\,(by^3 - cz^3)\,(2l^2x^3 + bcyz)$ we operate with δ or δ^2 only on the factor $2l^2x^3 + bcyz$; and in E' and E'' respectively, operating upon this factor, we obtain

$$-\tfrac{1}{4}\,\{4ll'x^3 + (bc' + b'c)\,yz\}, \quad \text{and} \quad \tfrac{1}{4}\,\{4l'^2x^3 + 2b'c'yz\},$$

viz. we thus obtain in E' the term

$$(abc + 8l^3)\,\xi^3\,(by^3 - cz^3)\,[l\,(abc + 2l^3)\,x^3 - 3bcl^2yz],$$

and in E'' the term

$$(abc + 8l^3)\,\xi^3\,(by^3 - cz^3)\,[(abc + 2l^3)^2x^3 + 18bcl^2yz].$$

30. $$E = -\tfrac{1}{9}\,\mathrm{Jac}\,(\overline{K},\ U,\ \Lambda), = -\tfrac{1}{3}\begin{vmatrix} \partial_x\overline{K}, & X, & \xi \\ \partial_y\overline{K}, & Y, & \eta \\ \partial_z\overline{K}, & Z, & \zeta \end{vmatrix}$$

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and, Σ omitting in $\overline{K}$ the factor $abc + 8\Omega$, we write $\overline{K} = Ax + By + Cz$, where

$$A = bc\xi^3 - 2ca\xi\eta^2 - 2ab\xi\zeta^2 - 2abc^2\eta\zeta, \text{ that is } = -\frac{1}{3}\begin{matrix} A, & X, & \xi \\ B, & Y, & \eta \\ C, & Z, & \zeta \end{matrix} \text{ which contains}$$

the term

$$\begin{aligned} \tfrac{1}{3}X \cdot B'_\eta - Cz \cdot &= \tfrac{1}{3}(ax^2 + 2lyz)\cdot\zeta\,(cxz^2 - 2abc\zeta^2 - 2cx\xi^2 - 2b\zeta^2\xi^2 \\ &\qquad - x(ab\zeta^2 - 2cx\zeta\xi^2 - 2cx\zeta^2 - 2x\xi^2\zeta^2 \\ &= (ax^2 + 2lyz)(cx^2 - b\zeta^2)(2\xi^2 + x\zeta). \end{aligned}$$

Hence, restoring the factor $abc + 8\Omega$, we have the terms

$$E = (abc + 8\Omega)\cdot x^2(cx^2 - b\zeta^2)\,[2a\xi^2 + a^2x\zeta] + yz(cx^2 - b\zeta^2)\,[4\xi^2 + 2ax\zeta]:$$

31 and 32. $\qquad E' = -\frac{1}{3}(\lambda)\,E. \quad E'' = -\frac{1}{3}(\mu)\,E:$

$\overline{E}$ is of the form $(abc + 8\Omega)(aU + bV + cW)$, and we operate with λ and μ on the factors $2a\xi^2 + a^2x\zeta$, &c.: viz. $\lambda(2a\xi^2 + a^2x\zeta) = 2(a\lambda' + a^2\xi^2 + 2ax\zeta$, $\mu(2a\xi^2 + a^2x\zeta) = 4a\xi^2 + 2a^2x\zeta$, and we thus obtain in $\overline{E}'$ the term

$$(abc + 8\Omega)\,x^2(cx^2 - b\zeta^2)\,[a(abc - 4\Omega)\,\xi^2 - 6a^2\Omega x\zeta],$$

and in $\overline{E}''$ the term

$$(abc + 8\Omega)\,x^2(cx^2 - b\zeta^2)\,[-3a^2(abc + 2\Omega)\,\xi^2 + 9a^2\Omega x\zeta].$$

25. $M = \frac{1}{36}\,\mathrm{Jac}\,(U, \Psi, \Lambda)$: this, omitting the factor $(abc + 8\Omega)^3$ of Ψ is

$$\begin{aligned} &ax^2 + 2lyz\,, \quad ax^2(ax^2 - 5by^2 - 5cz^2)\,, \quad \xi \\ = &\tfrac{1}{3} \quad by^2 + 2lzx\,, \quad by^2(by^2 - 5cz^2 - 5ax^2)\,, \quad \eta \\ &cz^2 + 2lxy, \quad cz^2\,(cz^2 - 5ax^2 - 5by^2), \quad \zeta \end{aligned}$$

the coefficient of ξ herein is

$$\begin{aligned} &= \tfrac{1}{3}\{(bxy^2z^2 + 2xlxz^2)(cz^2 - 5ax^2 - 5by^2) - (bxy^2z^2 + 2lxy^2)(by^2 - 5cz^2 - 5ax^2)\}, \\ &= \tfrac{1}{3}\{bxy^2z^2(-6by^2 + 6cz^2) + 2lx[-b^2y^4 + c^2z^4 + 5ax^2(by^2 - cz^2)]\}, \\ &= \quad (by^2 - cz^2)[5alx^4 - blxy^2 - clxz^2 - 3bcy^2z^2]. \end{aligned}$$

Hence, restoring the factor $(abc + 8\Omega)^3$, we have the term

$$(abc + 8\Omega)^3\,.\,\xi\,(by^2 - cz^2)[5alx^4 - blxy^2 - clxz^2 - 3bcy^2z^2].$$

26. $M' = -(\lambda)\,M$. Here M is of the form $(abc + 8\Omega)^3(a^2U + \&c.)$: and the λ operates through the $(abc + 8\Omega)^3a^2$, &c.; we in fact have in M' the term

$$-(abc + 8\Omega)^3\,.\,\xi\,(by^2 - cz^2)[5al'x^4 - bl'xy^2 - cl'xz^2 - 3bcy^2z^2],$$

which is

$$= (abc + 8\Omega)^3\,.\,\xi\,(by^2 - cz^2)[(abc + 2\Omega)(5ax^4 - bxy^2 - cxz^2) + 18bcl^2y^2z^2].$$

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33. $$\bar{M} = -\tfrac{1}{6}\,[\mathrm{Jac}]\,(P,\ F,\ \Lambda), = -\tfrac{1}{6}\begin{vmatrix} -3lbc\xi^3 + (-abc + 4l^3)\eta\zeta\,, & \partial_x F,\ x \\ -3lca\eta^3 + (-abc + 4l^3)\zeta\xi\,, & \partial_y F,\ y \\ -3lab\zeta^3 + (-abc + 4l^3)\xi\eta\,, & \partial_z F,\ z \end{vmatrix},$$

and the whole coefficient of x is thus

$$= \tfrac{1}{6}\,\{[3lca\eta^3 + (abc - 4l^3)\zeta\xi]\,\partial_x F - [3lab\zeta^3 + (abc - 4l^3)\xi\eta]\,\partial_\omega F\},$$

or substituting for $\frac{1}{6}\,\partial_x F$, $\frac{1}{6}\,\partial_\omega F$ their values, this is

$$\begin{aligned} &= \tfrac{1}{6}\{3lca\eta^3 + (abc - 4l^3)\zeta\xi\}\{a^3b^2\zeta^3 - (abc + 16l^3)(b\zeta^2\xi^3 + a\zeta^2\eta^3) \\ &\qquad - 4l^3(bc\xi^4\eta + ca\xi\eta^4 + 4ab\xi\eta\zeta^3) - 8l(abc + 2l^3)\xi^2\eta^2\zeta] \\ &- \tfrac{1}{6}\{3lab\zeta^3 + (abc - 4l^3)\xi\eta\}\{a^3c^2\eta^3 - (abc + 16l^3)(a\eta^2\zeta^3 + c\eta^2\xi^3) \\ &\qquad - 4l^3(bc\zeta\xi^4 + 4ca\xi\eta^3\zeta + ab\xi\zeta^4) - 8l(abc + 2l^3)\xi^3\eta\zeta^3\}. \end{aligned}$$

Collecting first the terms independent of $abc - 4l^3$, and next those which contain $abc - 4l^3$, each set contains the factor $c\eta^3 - b\zeta^3$, and the whole is $= c\eta^3 - b\zeta^3$ into

$$\begin{aligned} &- 3lc^2bc\eta^3\zeta^3 - 3a^3l(abc + 8l^3)\eta^3\zeta^3 - 12l^3(abc\xi^4 + a^3c\xi\eta^3 + a^3b\xi\zeta^3) - 24al^3(abc + 2l^3)\xi^2\eta\zeta \\ &\qquad + (abc - 4l^3)\{a^3c\xi\eta^3 + a^3b\xi\zeta^3 - (abc + 16l^3)\xi^4 + 12al^3\xi^2\eta\zeta\}; \end{aligned}$$

and here collecting the terms in ξ^4, $\xi(c\eta^3 + b\zeta^3)$, $\xi^2\eta\zeta$, and $\eta^3\zeta^3$, each of these contains the factor $abc + 8l^3$, and, finally, the term of $\bar{M}$ is

$$= (abc + 8l^3)(c\eta^3 - b\zeta^3)[(abc - 8l^3)\xi^4 - a^3c\xi\eta^3 - a^3b\xi\zeta^3 - 12al^3\xi^2\eta\zeta - 6a^3b\eta^3\zeta^3]\,x\,.$$

34. $$\bar{M}' = \tfrac{1}{6}\,(\delta)\,\bar{M}$$

$\bar{M}$ is here of the form $(abc + 8l^3)(aU + bV + cW)$; and, operating with δ through the $(abc + 8l^3)\,a$, &c., we obtain in $\bar{M}'$ the term

$$\tfrac{1}{6}\,(abc + 8l^3)\,x\,(c\eta^3 - b\zeta^3)[(a'bc + ab'c + abc' - 24l^2l')\,\xi^4 + \&c.],$$

where $a'bc + ab'c + abc' - 24l^2l' = 18abcl^2 + 24l^6\,(abc + 2l^6), = 6l^6\,(7abc + 8l^6)$, and the term thus is

$$= (abc + 8l^6)\,x\,(c\eta^3 - b\zeta^3)\,[(7abc + 8l^6)\,l^6\xi^4 \ldots].$$

This concludes the series of calculations.

CAMBRIDGE, ENGLAND, 17 *May*, 1881.

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On Certain Expansion Theorems.

By Emory McClintock, *F. I. A.*

I.

Any function fy can be expanded in terms (positive integral powers) of x, if $y = x\phi y$, provided fy and ϕy can be expanded in terms of y, and ϕy does not vanish with y; because x can, by dividing y by ϕy, be expressed in terms of y, and by reversion y, and therefore fy, in terms of x. These algebraic operations do not, however, disclose the law of the coefficients, which may be found in the following manner.

Assuming it known that $\mathrm{D}^{n-1}(\phi y)^n \mathrm{D}x^m_{(y=0)} = 0$ $\left(\text{where } \mathrm{D} = \frac{d}{dy}\right)$, unless $m = n$, when it becomes equal to $1 \cdot 2 \cdot 3 \ldots n$ or $n!$, we have, supposing $fy = a_0 + a_1 x + \frac{1}{1.2} a_2 x^2 + \ldots$,

$$\mathrm{D}^{n-1}(\phi y)^n \mathrm{D}fy_{(y=0)} = \mathrm{D}^{n-1}(\phi y)^n \mathrm{D}(a_0 + a_1 x + \ldots) = \frac{1}{n!} a_n n! = a_n;$$

also $f0 = a_0$, so that

$$fy = fy_{(y=0)} + x \cdot \phi y \mathrm{D}fy_{(y=0)} + \frac{1}{2} x^2 \cdot \mathrm{D}(\phi y)^2 \mathrm{D}fy_{(y=0)} + \ldots . \qquad (1)$$

For several reasons which will appear, I think this series will be found highly important. Lying midway between those of Lagrange and Bürmann, and transformable at once into either of those well-known series, the present result appears both simpler in form and easier of proof than either of them.

The correctness of the assumption upon which (1) is founded is readily shown. Since $x = y(\phi y)^{-1}$, or say $y\phi^{-1}$,

$$\mathrm{D}^{n-1}\phi^n \mathrm{D}x^m_{(y=0)} = \mathrm{D}^{n-1}\phi^n \mathrm{D}y^m \phi^{-m}_{(y=0)} = \mathrm{D}^{n-1}\phi^{n-m}\mathrm{D}y^m + \mathrm{D}^{n-1}\phi^n y^m \mathrm{D}\phi^{-m}_{(y=0)}.$$

If $m > n$, this vanishes, since y is a factor. If $m = n$, the second term vanishes, and there remains $\mathrm{D}^{n-1}\mathrm{D}y^n = n!$. If $m < n$, the whole expression again vanishes. We may write it $\mathrm{D}^{n-1}\phi^{n-m}my^{m-1} - \mathrm{D}^{n-1}y^m \frac{m}{n-m} \mathrm{D}\phi^{n-m}_{(y=0)}$. If we suppose this expanded in terms of y, all of the terms necessarily vanish,

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since $y = 0$, except the term independent of y. Supposing c to be the coefficient of y^{n-m} in the expansion of ϕ^{n-m}, the independent term will be

$$D^{n-1}cy^{n-m}my^{m-1} - D^{n-1}y^m \frac{m}{n-m}(n-m)cy^{n-m-1} = mcD^{n-1}y^{n-1} - mcD^{n-1}y^{n-1} = 0.*$$

I have said that (1) can be transformed at once into Lagrange's theorem. If $u = y + z$, $D_y fu = D_z fu$. In (1), let $fy = fu$, and $\phi y = \psi u$. Then $u = z + x\psi u$, and we have Lagrange's theorem, in its later form,

$$fu = fz + x \,.\, \psi z D_z fz + \frac{1}{1\,.\,2} x^2 \,.\, D_z(\psi z)^2 D_z fz + \ldots .$$

If $x = 1$, we have the same theorem in its original form,

$$fu = fz + \psi z D_z fz + \ldots ,$$

where $u = z + \psi u$. I have also said that (1) is simpler in form and easier of proof than Lagrange's theorem. As regards its form, it is almost identical with that case of Lagrange's theorem in which $z = 0$, and, consequently, $u = y = x\phi y$,

$$fy = fz_{(z=0)} + x \,.\, \phi z D_z fz_{(z=0)} + \ldots ,$$

a case declared by Lagrange himself, in comparison with that theorem, to be equally general and much more simple. Even this case of Lagrange's theorem is in form less simple than (1), because it introduces unnecessarily a third quantity, z, in addition to those given by the conditions of the problem, x and y. I am disposed to regard (1) as new and distinct, not only on account of this slight difference of form, but also, and chiefly, on account of its origin, diametrically opposite to that of the series just referred to; the one being a casual deduction from a more complex expression, retaining a remnant of its complexity in the unnecessary variable z, the other being, of and by itself, a simple and complete solution of the general problem of reversion. As regards demonstration, it is to be remarked that Lagrange's theorem has not been found easy to prove. By far the best and simplest demonstration, of many which I have met, is that of Laplace, usually followed by the text-books. Concerning it, we may observe that it assumes Maclaurin's theorem; that it proceeds, step by step, from one degree to the next higher; and that it keeps up a cross-fire of differentiations with respect to different variables. Concerning the proof of (1) we may remark that it involves, in the most elementary manner, a few of the most elementary

* We might modify the demonstration by beginning with

$$D^{n-1}\phi^n Dx^m = D^n\phi^n x^m - D^{n-1}x^m D\phi^n ,$$

both of which terms vanish when $m > n$, and the second when $m = n$, since $x = 0$ when $y = 0$, and x remains as a factor. When $m < n$, the term independent of y is

$$D^{n-m}cy^{n-m} - D^{n-1}y \frac{n}{n-m} Dcy^{n-m} = cD^n y^n - cD^{n-1}ny^{n-1} = 0 .$$

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principles, and announces at once the value of the general term. It has also the merit of indicating at the start the class of functions to which it is applicable. By means of it we may observe that Lagrange's theorem can be employed when fu and ψu can be expanded in terms of $y = u - z$, provided ψu does not vanish when $u = z$. Of course fu and ψu, or $f(y + z)$ and $\psi(y + z)$, can be expanded in terms of y in all cases to which Taylor's theorem applies.

I have said, on the other hand, that (1) can be transformed at once into Bürmann's theorem. Let x be any function of t, and let $fy = ft$; then, since $\phi y = \frac{y}{x}$, (1) becomes Bürmann's first theorem,

$$ft = ft_{[y=0]} + x \cdot \frac{y}{x} \mathrm{D}_y ft_{[y=0]} + \ldots .$$

I call this "first" because two other series sometimes get the name of "Bürmann's theorem." It was devised for the purpose of expanding one function of t in terms of another. Published in 1796, it was long regarded as not only different from, but more comprehensive than, that of Lagrange.*

Bürmann himself showed that Lagrange's theorem can be readily derived from his own. The converse, as will be seen, is equally true. Bürmann's proof of his theorem, the only demonstration of it with which I have met, may be found in Lacroix's Appendix and in Grunert's Supplement to Klügel's Wörterbuch, as well as in the works cited in the footnote. It occupies five of Grunert's pages. There can be no doubt of the correctness of my statement that (1) is both simpler in form and easier of proof than Bürmann's theorem.

We have, then, in (1) a series which is essentially identical with those of Lagrange and Bürmann, which is simpler in form than either, and which is at once a connecting link between them and a necessary step in the most direct demonstration of both. The inference seems warranted that we should regard it as the main proposition, of which the others are corollaries. This inference will be strengthened when we see how readily other corollaries can be deduced from it, which are usually referred to Lagrange's and Bürmann's theorems.

For instance, let $v = \psi(z + y)$, $\phi y = \chi v = \chi\psi(z + y)$, and $fy = fv = f\psi(z + y)$. Then $v = \psi(z + x\chi v)$, and since, with regard to any function of $z + y$, $\mathrm{D}_y = \mathrm{D}_z$, we have from (1) Laplace's theorem,

$$fv = f\psi z + x \cdot \chi\psi z \mathrm{D}_z f\psi z + \ldots .$$

* See the Encyclopædia Metropolitana. Article *Integral Calculus*, part 3, p. 89; De Morgan. *Calculus*, pp. 303–305. In the appendix to the *Calculus*, p. 774, De Morgan says, however, "Bürmann's theorem is nothing but Lagrange's," and proves it concerning Bürmann's second theorem.

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Again, let $y = u - a$, $\mathfrak{f}y = fu$, $x = \dfrac{u-a}{\varphi(u-a)} = \psi u$, so that $\phi y = \dfrac{u-a}{\psi u}$, and we have from (1) what we may call Bürmann's second theorem,

$$fu = fu_{[u=a]} + \psi u \,.\, \frac{u-a}{\psi u}\, \mathfrak{D} fu_{[u=a]} + \ldots .$$

This "very remarkable formula," as Lacroix and others style it, gives explicitly the development of one function, fu, in terms of another, ψu.

Another of Bürmann's series may be derived from (1) by substituting for y, $u-a$; for x, $\psi u - \psi a$; for ϕy, $\dfrac{u-a}{\psi u - \psi a}$; and for $\mathfrak{f}y$, fu.

Nearly seventy years ago, M. Wronski published a theorem for development, afterwards characterized by De Morgan as "excessively general," "elegant," "really remarkable." For this theorem, Professor Cayley has presented (*Quarterly Journal*, xii, 221) a simpler substitute, as follows:

"Suppose, in general, $\phi x = (x-a)\,\psi x$, or let the equation be $(x-a)\,\psi x + \lambda f x = 0$, that is, $x - a + \lambda \dfrac{fx}{\psi x} = 0$; we have then, by Lagrange's theorem,

$$Fx = F - \frac{\lambda}{1} F' \frac{f}{\psi} + \frac{\lambda^2}{1.2} \left\{ F' \left(\frac{f}{\psi}\right)^2 \right\}' - \frac{\lambda^3}{1.2.3} \left\{ F' \left(\frac{f}{\psi}\right)^3 \right\}'' + \&c.$$

Consider, for example, the term $\left\{ F' \left(\dfrac{f}{\psi}\right)^3 \right\}''$; this is $= \left\{ F'x \,.\, \dfrac{(x-a)^3 (fx)^3}{(\psi x)^3} \right\}''$, the accents denoting differentiation in regard to x, and x being ultimately put $= a$; or, what is the same thing, it is $= \left(\dfrac{d}{d\theta}\right)^2 \left[F'(a+\theta)\, \dfrac{\theta^3 \{f(a+\theta)\}^3}{\{\psi(a+\theta)\}^3} \right]$, the accents now denoting differentiation in regard to θ, and this being ultimately put $= 0$. This is

$$\left(\frac{d}{d\theta}\right)^2 \left[F'(a+\theta)\, \frac{\{f(a+\theta)\}^3}{(\psi' a + \frac{\theta}{1.2}\, \psi'' a + \ldots)} \right].$$

This may be written $\left(F' f^3 \,.\, \dfrac{1}{A^3} \right)''$, where $A = \phi' + \dfrac{1}{2}\, \theta\phi'' + \dfrac{1}{6}\, \theta^2 \phi''' + \ldots$, it being understood that as regards $F' f^3$, which is expressed as a function of a only (θ having been therein put $= 0$), the exterior accents denote differentiations in respect to a, whereas, in regard to A, $= \phi' + \dfrac{1}{2}\, \theta\phi'' +$ &c., they denote differentiation in regard to θ, which is afterwards put $= 0$. And the theorem thus is

$$Fx = F - \frac{\lambda}{1} \left(F' f \,.\, \frac{1}{A} \right) + \frac{\lambda^2}{1.2} \left(F' f^2 \,.\, \frac{1}{A^2} \right)' - \frac{\lambda^3}{1.2.3} \left(F' f^3 \,.\, \frac{1}{A^3} \right)'' + \&c."$$

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The noteworthy result thus derived by Professor Cayley may be obtained from (1) in a very direct manner as follows. Given $x = y f(x)$, and $\varphi x = u$, to develop $f x$ in terms of x. Let $y = z - a$, and

$$\varphi x = \frac{y}{x} = \frac{y f z}{z} = \frac{y f(y+a)}{y+a} = \frac{f(y+a)}{a + \frac{1}{2} y + \dots}$$

Then (1) becomes

$$f x = f(y+a)_{y=0} + x \cdot \varphi x \{f(y+a)_{y=0} + \frac{1}{1.2} x \varphi x \{f(y+a)_{y=0} + \dots$$

II.

Of the various other forms following from (1), two are of great practical importance, and are apparently perfect in form and substance, incapable of amendment. I refer, of course, to Lagrange's and Laplace's theorems. The several series proposed by Birmann as available in developing one function in terms of another do not seem to be quite so perfect. They accomplish nothing which cannot be done with suitable transformations by either of these theorems or by (1). Their value, therefore, lies entirely in the help which they afford by indicating what transformations may be necessary, and by furnishing the results of such transformations. If we have to expand fu in terms of φu, and if φx happens to be readily divisible by $u - a$, Birmann's second form will be immediately available and of course useful. If φx is not more likely to be at once conveniently divisible by $u - a$, we may perhaps turn to Birmann's first theorem, which relates to the finding of some function of u which vanishes with φx, in a form which is rather vague, and as a matter of a trial process, most mathematicians will prefer to leave Birmann's series alone, and to employ one of the other more familiar theorems, deriving at the moment such transformations as may seem necessary. There is however a formula applicable to a large number of cases, which seems to have escaped the notice of Birmann and other writers, and which is worth, I think, the trouble of use if it be borne in mind by those who have occasion to deal with developments of the kind in question.

Suppose φx equal to a series $f(x, \beta x, \gamma x, \dots)$ of the form $\varphi x = a$ when $x = 0$, and $\beta x = 0$ when $x = 0$. Then

$$f x = f_{x=0} + \beta x \cdot \frac{\partial f}{\partial \beta x} + \frac{1}{1.2} (\beta x)^2 \frac{\partial^2 f}{\partial (\beta x)^2} + \dots + \frac{1}{\lambda} (\beta x)^\lambda \frac{\partial^\lambda f}{\partial (\beta x)^\lambda} + \dots \quad (2)$$

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the general term being $\frac{1}{1.2.\ldots.m}(fu)^m . D^{m-1}\left(\frac{y-a}{f\psi y}\right)^m D f\psi y$. If, in applying this rule, we find that fu can be conveniently divided by $u-a$, the series becomes equivalent, as a special case, to Bürmann's second theorem, which it thus practically replaces. As an illustration, let $fu = u^6 - au^3$. Here fu is divisible by $u^4 - a$, so that $\psi^{-1}u = u^4$, $\psi u = u^{\frac{1}{4}}$, and $\frac{y-a}{f\psi y} = (y-a) \div (y^{\frac{3}{2}} - ay^{\frac{1}{2}}) = y^{-\frac{1}{2}}$. Hence,

$$fu = fa^{\frac{1}{4}} + fu \,.\, a^{-\frac{1}{4}} D_a f a^{\frac{1}{4}} + \frac{1}{1.2}(fu)^2 . D_a a^{-\frac{1}{4}} D_a f a^{\frac{1}{4}} + \ldots .$$

The series (2) is derived from (1) by putting $x = fu$, $y = \psi^{-1}u - a$, $\left(\text{whence } u = \psi(y+a),\ \phi y = \frac{y}{x} = \frac{y}{f\psi(y+a)},\ fy = fu = f\psi(y+a)\right)$, and finally writing $y - a$ for y, throughout. It may also be derived very readily from Laplace's theorem, to which it bears exactly the same relation as that borne to Lagrange's by Bürmann's second theorem. Whether there is any real necessity for an explicit formula, distinct from Laplace's theorem, for dealing with this subject, may be questioned. Bürmann and many other writers have thought it desirable to have one or more. The present formula appears to meet the requirement.

III.

Among the questions to which (1) is directly applicable, one of the most important is that of the common reversion of series. Expressed most simply, this question is, given $x = y + ay^2 + by^3 + \ldots$, to expand y in terms of x. Here $y = x\phi y$, where ϕy is the reciprocal of $1 + ay + by^2 + \ldots$, or $(1 + ay + \ldots)^{-1}$, and from (1) we have

$$y = x + \frac{1}{2}x^2 . D(\phi y)^2|_{y=0} + \ldots .$$

This is the same result, of course, as that usually derived from Lagrange's theorem, with the merely formal difference that y takes the place of z in the second member. The determination of the coefficients is a matter of some difficulty; so much so that on several occasions on which extensions have been made to the known portion of the series, the name of the calculator has been recorded, The latest calculation appears to have been that made by De Morgan (Penny Cyclopædia, Article *Reversion of Series*), who describes the process devised by him to facilitate the work.

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It has, perhaps, not been noticed that, having given the series

$$\frac{1}{x} = \frac{1}{y} + \alpha y + \beta y^2 + \dots.$$

it is peculiarly easy to expand y in terms of x. Here we have, as before, $y = x\phi y$, and

$$y = x + \frac{1}{2}\, x^2.\, \mathrm{D}\,(\phi y)^2_{[y=0]} + \dots.$$

but in this case $\phi y = 1 + \alpha y^2 + \beta y^3 + \dots$, and the coefficients are simpler and easier to determine. In the former instance,
$y = x - \alpha x^2 - (b - 2a^2)x^3 - (c - 5ab + 5a^3)x^4 - (d - 3b^2 - 6ac + 21a^2b - 14a^4)x^5 - \dots$;
while in the present,

$$y = x + \alpha x^3 + \beta x^4 + (\gamma + 2a^2)\, x^5 + (\delta + 5a\beta)\, x^6 + \dots. \qquad (3)$$

Either result may be derived from the other by putting $a = -\alpha x$, $b = -\beta x$, &c. In another light, we may regard (3) as the development of a root of the equation $1 - \frac{y}{x} + \alpha y^2 + \beta y^3 + \dots = 0$, in descending powers of the coefficient of y. When this equation has a very small root, the series may be employed for its arithmetical computation, though it is not so good for that purpose as the other series, produced by reversion.

My chief purpose in presenting (3) is to show how it may be employed in facilitating the determination of the usual reversion-coefficients, by a method even less laborious than that pursued by De Morgan. The reason why the coefficients of (3) are, in comparison with those of the other series, so easy to determine is two-fold: first, ϕy is not a fraction, and secondly, $\mathrm{D}\phi y$ vanishes when $y = 0$. In consequence of these favoring circumstances, the coefficients may, by the help of the combinatorial analysis (see De Morgan, *Calculus*, pp. 335, 336), be written down almost at will. To find the coefficient of x^m, let us first see how y^{m-1} can be resolved into factors of the form $y^2, y^3, \dots y^{m-1}$. If for example, $m = 10$, we find that y^9 can be resolved in several ways, as follows: $y^2, y^2y^7, y^3y^6, y^4y^5$, $y^2y^3y^4$, $y^2y^2y^5$, $y^2y^3y^4$, $y^2y^2y^3y^2$. Each of these expressions stands for a term or element of the result, it being understood that instead of each power of y we must write its coefficient in $1 - \frac{y}{x} + \alpha y^2 + \beta y^3 + \dots = 0$. Thus θ, $\alpha\zeta$, $\beta\varepsilon$, $\gamma\delta$, $\alpha^3\delta$, $\alpha\beta\gamma$, β^3, and $\alpha^3\beta$ will be elements in the case chosen. To each element thus found, containing more than one factor, a numerical coefficient is to be annexed. Each element being of the form $\alpha^r\beta^s\gamma^t \dots$, its coefficient will be

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$\frac{(m-1)(m-2)\ldots(m-n+1)}{r!\ s!\ t!\ \ldots}$, where $n = r + s + t + \ldots$. Thus, the coefficient of $\alpha\beta\gamma$ is $9 \cdot 8 = 72$; that of $\alpha^2\delta$ is $\frac{9 \cdot 8}{2} = 36$, and so in other cases. The result, in the case chosen, may thus be written out:

Coefficient of $x^{10} = \theta + 9(a\zeta + \beta\epsilon + \gamma\delta) + 36\alpha^2\delta + 72\alpha\beta\gamma + 12\beta^3 + 84\alpha^2\beta$.

If, therefore, it is desired to determine the reversion-coefficients as far as those of x^m inclusive, we must find the coefficients of (3) in this way as far as the mth power, and also certain elements of the coefficients of higher powers (namely, those elements of the coefficient of each higher power, say x^{m+r}, for which n is not less than r), and then put $\alpha = -\frac{a}{x}$, $\beta = -\frac{b}{x}$, and so on.

The process thus indicated will give the expansion of y, where $x = y + ay^2 + by^3 + \ldots$. If the given series is $x = c_1 y + c_2 y^2 + c_3 y^3 + \ldots$, it can be reduced to the first form by dividing both members by c_1, when y can be expanded in terms of $\frac{x}{c_1}$.

IV.

Lagrange's and Laplace's theorems can be demonstrated by the means employed in proving (1), without explicitly naming the latter as a step in the process. In doing so, however, we cannot fail to be impressed with the fact that we are not treating the subject in the best and simplest manner. For Laplace's theorem, the proof would be as follows.

If $f\psi(y + z)$ and $\phi\psi(y + z)$ can be expanded in terms (positive integral powers) of y, and if $\phi\psi z$ is not 0, and if $x = y \div \phi\psi(y + z)$, then can x be expanded in terms of y, and by reversion y, and therefore $f\psi(y + z)$, in terms of x. It is required to determine the coefficients in the latter case. That is to say, it is required to determine the general form of a_n in

$$f\psi(y + z) = a_0 + x \cdot a_1 + \frac{1}{1 \cdot 2} x \cdot a_2 + \ldots.$$

Let it be shown, as before, that the expression $D_y^{n-1}[\phi\psi(y + z)]^n D_y x^m$ vanishes when $y = 0$, unless $m = n$, when it is equal to $n!$. Then

$$D_y^{n-1}[\phi\psi(y + z)]^n Df\psi(y + z)_{(y=0)} = D_y^{n-1}[\phi\psi(y + z)]^n D(a_0 + x \cdot a_1 + \ldots)$$

$$= \frac{1}{n!} a_n n! = a_n.$$

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Since $v_n f(y+z) = v_n f(y+z)$, this expression is equivalent to

$$a_n = v_n^{-1} \varphi_0 \varphi^n f \psi_0 z.$$

Also, $a_0 = f\psi_0 z$, since $y = 0$ when $x = 0$. Let $u = \downarrow y + z$; then, since $y = x\varphi\downarrow$, $y + z = x\varphi u$, we have $u = \downarrow z + x\varphi u$, and our first equation becomes

$$fu = f\psi_0 z + x \cdot \varphi_0 v_0 f\psi_0 z + \dots,$$

which is Lagrange's theorem.

For Lagrange's theorem, the proof would be the same, omitting throughout the functional symbol $\downarrow$.

MILWAUKEE, May 14, 1891.

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Some Theorems in Numbers.

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§1. *On the Residues mod. k of the Symmetric Functions of the Numbers less than k, where k = any Integer.*

In the following $\equiv$ will denote identical congruity, *i. e.*, $\phi(x) \equiv \psi(x)$, mod. k, will denote that the coefficients of corresponding powers of x are respectively congruous to one another mod. k. If $\Pi(x-\alpha)$ denote the product $(x-1)(x-2)(x-3)\ldots(x-a+1)$, where a is a prime number, we know that $\Pi(x-\alpha) \equiv x^{a-1}-1$ mod. a. This expresses the fact that the symmetric functions $\Sigma\alpha$, $\Sigma\alpha\beta$, $\Sigma\alpha\beta\gamma$, &c. of the numbers less than (and prime to) a are each $\equiv 0$ mod. a, except the last, which is $\equiv -1$ mod. a. It is proposed in this section to determine the value of $\Pi(x-\alpha)$ for any integer, k, $= a^\iota b^\kappa \ldots g^\varkappa h^\varpi \ldots q^\iota$, where a, b, &c. are prime numbers; or, more generally, to determine the residue, mod. k, of $\Pi(x-\theta_s)$, where θ_s, θ_s', θ_s'', &c. are those numbers less than k which contain $s = hi \ldots q$, and no prime factor of k not found in s. These numbers were called in my former paper, Vol. 3, No. 4, of this Journal, the s-totitives of k. The number of them was called the s-totient of k, and denoted by $\tau_s(k)$. It was there seen that $\tau_s(k) = a^{\iota-1}b^{\kappa-1}\ldots q^{\iota-1}(a-1)(b-1)\ldots(g-1)$.

Theorem I. If $\Pi_{a^\iota}(x-\theta_1)$ denote the product $(x-\theta_1')(x-\theta_1'')(x-\theta_1''')\ldots$, where the numbers θ_1 are the prime totitives of a^ι, a being an odd prime number, then

$$\Pi_{a^\iota}(x-\theta_1) \equiv (x^{a^{\iota-1}}-1)^{a^{\iota-1}} \text{ mod. } a^\iota;$$

and if θ_a', θ_a'', &c. be the a-totitives of a^ι, then

$$\Pi_{a^\iota}(x-\theta_a) \equiv x^{a^{\iota-1}} \text{ mod. } a^\iota.$$

To prove the theorem it will be shown first that

$$\Pi_{a^\iota}(x-\theta_1) \equiv [\Pi_{a^{\iota-1}}(x-\theta_1)]^a \text{ mod. } a^\iota.$$

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Let $\alpha, \beta, \gamma, \ldots \omega$ be the prime totitives of a^{t-1}; then the prime totitives of a^t will be given by $\alpha + \lambda a^{t-1}$, $\beta + \lambda a^{t-1}$, &c., where λ has all values from 0 to $a-1$. Now

$$\Pi(x-\alpha-\lambda a^{t-1}) \equiv x^a - (C_1^a\alpha + A a^{t-1})x^{a-1} + (C_2^a\alpha^2 + C_1^{a-1}A a^{t-1}\alpha)x^{a-2} - (C_3^a\alpha^3 + C_2^{a-1}A a^{t-1}\alpha^2)x^{a-3} + \&c. \text{ mod. } a^t,$$

where the terms containing $a^{2(t-1)}$, $a^{3(t-1)}$, &c. have been dropped, and C_1^a, C_2^a, &c. are the successive binomial coefficients of the a^{th} power, and $A = 0 + 1 + 2 + 3 + \ldots + (a-1) = \frac{a(a-1)}{2}$. But $A \equiv 0 \bmod a$. $\therefore Aa^{t-1} \equiv 0 \bmod a^t$, and

$$\Pi(x-\alpha-\lambda a^{t-1}) \equiv (x-\alpha)^a \bmod a^t.$$

$$\therefore \Pi_a(x-\theta_1) \equiv (x-\alpha)^a(x-\beta)^a \ldots (x-\omega)^a \equiv [\Pi_{a^{t-1}}(x-\theta_1)]^a \bmod a^t.$$

Now,

$$\Pi_a(x-\theta_1) \equiv x^{a-1} - 1 \bmod a,$$

$$\therefore \Pi_{a^2}(x-\theta_1) \equiv (x^{a-1}-1)^a \equiv x^{a(a-1)} - a^2,$$

$$\therefore \Pi_{a^3}(x-\theta_1) \equiv (x^{a-1}-1)^{a^2} \equiv x^{a(a-1)} - a^3,$$

$$\therefore \Pi_{a^t}(x-\theta_1) \equiv (x^{a-1}-1)^{a^{t-1}} \equiv x^{a(a-1)} - a^t,$$

and the first part of the theorem is proved. The same proof applies to the second part of the theorem, if we suppose α, β, &c. to be not the prime totitives, but the a-totitives of a^{t-1}. Then we get, just as before,

$$\Pi_{a^t}(x-\theta_a) \equiv [\Pi_{a^{t-1}}(x-\theta_a)]^a \bmod a^t.$$

But we have

$$\Pi_a(x-\theta_a) \equiv x - 0,$$

$$\therefore \Pi_{a^2}(x-\theta_a) \equiv x^a \bmod a^2, \text{ \&c.},$$

$$\therefore \Pi_{a^t}(x-\theta_a) \equiv x^{a^{t-1}} \bmod a^t. \quad \text{Q. E. D.}$$

If, in the foregoing, we put $a = 2$, then

$$\Pi(x - \alpha \pm 2^{t-2}\lambda) \equiv x^2 - (2\alpha \pm 2^{t-1})x + (\alpha^2 \pm 2^{t-1}) \bmod 2^t,$$

since $A = 0 + 1 \equiv \pm 1 \bmod 2$. This may be written

$$\Pi(x - \alpha \pm 2^{t-2}\lambda) \equiv (x-\alpha)^2 \pm 2^{t-1}(x-1) \bmod 2^t.$$

$$\therefore \Pi_{2^t}(x-\theta_1) \equiv \{(x-\alpha)^2 \pm 2^{t-1}(x-1)\}\{(x-\beta)^2 \pm 2^{t-1}(x-1)\} \ldots .$$
$$\ldots \{(x-\omega)^2 \pm 2^{t-1}(x-1)\} \bmod 2^t.$$

$$\therefore \Pi_{2^t}(x-\theta_1) \equiv [\Pi_{2^{t-1}}(x-\alpha)^2 \pm 2^{t-1}(x-1)\{(x-\beta)^2(x-\gamma)^2 \ldots (x-\omega)^2$$
$$+ (x-\alpha)^2(x-\gamma)^2 \ldots (x-\omega)^2 + \ldots + (x-\alpha)^2(x-\beta)^2(x-\gamma)^2 \ldots (x-\overline{\omega-1})^2\} \bmod 2^t.$$

Now, if $t > 2$, the number of the prime totitives of 2^{t-1} is even, i. e., α, β, &c. are the 2^{t-2} odd numbers from 1 to $2^{t-1}-1$. Thus, we have

$$\Pi_{2^t}(x-\theta_1) \equiv [\Pi_{2^{t-1}}(x-\theta_1)]^2 \pm 2^{t-1}(x-1)2^{t-2}(x-1)^{2^{t-2}-1} + 2f(x)\} \bmod 2^t.$$

$$\therefore \Pi_{2^t}(x-\theta_1) \equiv [\Pi_{2^{t-1}}(x-\theta_1)]^2 \bmod 2^t, \text{ when } t > 2.$$

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If α, β, γ, &c. be the 2-totitives of 2^{t-1}, *i. e.*, the 2^{t-2} even numbers from 0 to $2^{t-1}-2$, then we get, as before,

$$\Pi_{2^t}(x-\theta_2) \equiv [\Pi_{2^{t-1}}(x-\theta_2)]^2 \pm 2^{t-1}(x-1)\{2^{t-2}x^{2^{t-1}-2}+2\phi(x)\} \text{ mod. } 2^t$$
$$\therefore \Pi_{2^t}(x-\theta_2) \equiv [\Pi_{2^{t-1}}(x-\theta_2)]^2 \text{ mod. } 2^t, \text{ when } t>2.$$

By inspection, we have

$$\Pi_2(x-\theta_1) = x-1,$$
$$\Pi_4(x-\theta_1) \equiv x^2-1 \text{ mod. } 4,$$
$$\therefore \Pi_8(x-\theta_1) \equiv (x^2-1)^2 \text{ mod. } 8,$$

and thence, by induction,

$$\Pi_{2^t}(x-\theta_1) \equiv (x^2-1)^{2^{t-2}} \text{ mod. } 2^t.$$

So we have, by inspection,

$$\Pi_2(x-\theta_2) = x,$$
$$\Pi_4(x-\theta_2) = x(x-2)$$
$$\therefore \Pi_8(x-\theta_2) \equiv x^2(x-2)^2 \text{ mod. } 8,$$
$$\therefore \Pi_{16}(x-\theta_2) \equiv x^4(x-2)^4 \text{ " } 16,$$
$$\therefore \Pi_{2^t}(x-\theta_2) \equiv [x(x-2)]^{2^{t-2}} \text{ mod. } 2^t.$$

This last expression may evidently be written

$$\Pi_{2^t}(x-\theta_2) \equiv x^{2^{t-1}-2}(x^2+2^{t-1}x+2^{t-1}) \text{ mod. } 2^t.$$

Thus we have

Theorem II. If $\Pi(x-\theta_1)$ denote the continued product $(x-\theta_1')(x-\theta_1'')\ldots$, where the numbers θ_1 are the successive odd numbers from 1 to 2^t-1, then, t being >1,

$$\Pi(x-\theta_1) \equiv (x^2-1)^{2^{t-2}} \text{ mod. } 2^t;$$

and if $\Pi(x-\theta_2)$ denote a similar product where the numbers θ_2 are the successive even numbers from 0 to 2^t-2, then, t being >2,

$$\Pi(x-\theta_2) \equiv [x(x-2)]^{2^{t-2}} \equiv x^{2^{t-1}-2}(x^2+2^{t-1}x+2^{t-1}) \text{ mod. } 2^t.$$

Example of Theorem I. Suppose $a^t = 27$. Then

$$(x-1)(x-2)(x-4)(x-5)(x-7)(x-8)(x-10)(x-11)(x-13)$$
$$(x+13)(x+11)\ldots(x+1)$$
$$\equiv (x^2-1)(x^2-10)(x^2-19)(x^2-4)(x^2-7)(x^2-16)(x^2-22)(x^2-25)(x^2-13)$$
$$\equiv (x^2-1)^9(x^4-11x^2+1)^9 \equiv (x^4-12x^2+12x^2-1)^9 \equiv (x^2-1)^9 \text{ mod. } 27.$$

That is, $\Pi(x-\theta_1) \equiv (x^2-1)^{3^2}$ mod. 3^3. So,

$$\Pi(x-\theta_2) = (x-0)(x-3)(x-6)\ldots(x+6)(x+3) \equiv x^9 \text{ mod. } 27.$$

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Example of Theorem II. Suppose $2^t = 16$. Then

$\Pi(x-\theta_s) \equiv (x-1)(x-3)(x-5)(x-7)(x-9)(x-11)(x-13)(x-15)$
$\equiv (x^2-1)^2(x^2-9)^2 \equiv (x^2-10)x^2+9)^2 \equiv x^4-4x^2+6x^2-4x^2+1 \equiv (x^2-1)^4 \bmod 16.$
So, $(x-\theta_1)(x-2)(x-4)(x-6)(x-8)(x+6)(x+4)(x+2) \equiv x^2(x-8)^2(x^2-4)^2$
$x^2(x^2+8x+16)^2 \equiv [x(x-2)]^4 \bmod 16.$

In the following, if $k = a^\alpha b^\beta \ldots g^\gamma h^\eta \ldots q^\kappa$, and $s = hi \ldots q$, R_s will denote that one of the roots of $x^\phi \equiv x \bmod k$, which is an s-totitive of k. (For the properties of these roots or repetents, see my paper, Vol. III, No. 4, of this Journal.) R_s will denote that repetent of k whose subscript contains all those prime factors of k not found in s. Thus R_1 will denote briefly the same thing as $R_{ai \ldots q}$. We can now prove the general theorem concerning the function $\Pi_k(x-\theta_s)$ of any integer k.

Theorem III. If $k = a^\alpha b^\beta \ldots g^\gamma h^\eta \ldots q^\kappa$, where a, b, &c. are different prime numbers, and if $s = h \ldots q$, $\sigma = h^\eta \ldots q^\kappa$, and θ_s, θ_σ, &c. be the s-totitives of k, then

$$\Pi_s(x-\theta_s) \equiv R_a(x^{\phi(a^\alpha)}-1)^{\nu(a^\alpha)} + R_b(x^{\phi(b^\beta)}-1)^{\nu(b^\beta)} + \ldots + R_g(x^{\phi(g^\gamma)}-1)^{\nu(g^\gamma)} + R_s x^{\nu(k)} \bmod k;$$

except (1) when $\frac{k}{a} = 4$ or a higher power of 2, in which case

$$\Pi_k(x-\theta_s) \equiv R_2(x^2-1)^{\frac{1}{2}\nu(k)} + R_s x^{\nu(k)} \bmod k,$$

and (2) when $\frac{k}{a^\alpha} = 1$ and $a^\alpha = 2^t$ where $t =$ or > 2, in which case, if $t = 2$, then

$$\Pi_k(x-\theta_s) \equiv x^{\nu(k)} + \tfrac{1}{2} k x^{\nu(k)-1} \bmod k.$$

and if $t > 2$, then

$$\Pi_k(x-\theta_s) \equiv x^{\nu(k)} + \tfrac{1}{2} k x^{\nu(k)-1} + \tfrac{1}{2} k x^{\nu(k)-2} \bmod k.$$

To prove the theorem, let us consider each component of the modulus separately. With respect to mod. a^α, the formula to be proved reduces to

$$\Pi_k(x-\theta_s) \equiv (x^{\phi(a^\alpha)}-1)^{\nu(k)} \bmod a^\alpha,$$

since R_b, R_c, ... R_g, R_s each contain a^α, and $R_a \equiv 1$, mod. a^α. Now it is clear that if we take the residues mod. a^α of the numbers θ_s we shall get each prime totitive of a^α the same number of times, and shall consequently get, in all, $\frac{\tau_1(k)}{\tau_1(a^\alpha)}$ groups, each group containing all the prime totitives of a^α. If

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$\Pi_a(x-\theta_s)$ denote the product taken for those numbers θ_s which compose any one of these groups, then by Theorem I

$$\Pi_{a^t}(x-\theta_s) \equiv (x^{a^{t-1}}-1)^{a^{t-1}} \text{ mod. } a^t,$$

if a be an odd prime number. Hence

$$\Pi_k(x-\theta_s) \equiv (x^{a^{t-1}}-1)^{a^{t-1}\cdot\frac{\tau_a(k)}{\tau(a^t)}} \text{ mod } a^t,$$

or

$$\Pi_k(x-\theta_s) \equiv (x^{a^{t-1}}-1)^{\tau_a(k)} \text{ mod. } a^t.$$

If $a=2$, we have, by Theorem II,

$$\Pi_{2^t}(x-\theta_s) \equiv (x^2-1)^{2^{t-1}} \text{ mod. } 2^t,$$

$$\therefore \Pi_k(x-\theta_s) \equiv (x^2-1)^{2^{t-1}\cdot\frac{\tau_2(k)}{2^{t-1}}} \text{ mod. } 2^t.$$

Now, if $\frac{k}{\sigma}$ contain at least one odd prime number, then $2^{t-2}\cdot\frac{\tau_2(k)}{2^{t-1}}\left(=\frac{1}{2}\,\tau_{2^t}(k)\right)$ is divisible by 2^{t-1}; but $(x^2-1)^{2^{t-1}}=(x-1)^{2^{t-1}}(x-1+2)^{2^{t-1}}$, and $(x-1+2)^{2^{t-1}} \equiv (x-1)^{2^t} \text{ mod. } 2^t$, therefore $(x^2-1)^{2^{t-1}} \equiv (x-1)^{2^t} \text{ mod. } 2^t$. Therefore,

$$\Pi_k(x-\theta_s) \equiv (x-1)^{\tau_2(k)} \text{ mod. } 2^t.$$

But if $\frac{k}{\sigma}=4$, or a higher power of 2, according to exception (1), then we have, as above,

$$\Pi_k(x-\theta_s) \equiv (x^2-1)^{\frac{1}{2}\tau_{2^t}(k)} \text{ mod. } 2^t.$$

Having shown that the formula holds true for mod. a^t, we have shown it true for mod. $\frac{k}{\sigma}$, since no distinction is to be made among $a,\ b,\ \ldots\ g$.

Let us now consider one of the components of σ, as q^s. The formula to be proved reduces to

$$\Pi_k(x-\theta_s) \equiv x^{\tau_{q^s}(k)} \text{ mod. } q^s,$$

since $R_{\overline{r}} \equiv 1$ mod. q^s, and $R_a\ R_b\ .\ .\ R_g$ each contain q^s. The numbers θ_s all contain q, and it is clear that, if we take their residues mod. q^s, we shall get each q-totitive of q^s the same number of times, and shall consequently get, in all, $\frac{\tau_q(k)}{q^{s-1}}$ groups, each group containing all the q-totitives of q^s. If $\Pi_{q^s}(x-\theta_s)$ denote the product taken for those numbers θ_s which compose any one of these groups, then, by Theorem I, we have, when q is odd,

$$\Pi_{q^s}(x-\theta_s) \equiv x^{q^{s-1}} \text{ mod. } q^s.$$

$$\therefore\ \Pi_k(x-\theta_s) \equiv x^{\tau_q(k)} \text{ mod. } q^s.$$

But if $q=2$, we have, by Theorem II, second part,

$$\Pi_{2^s}(x-\theta_s) \equiv (x(x-2))^{2^{s-2}} \text{ mod. } 2^s.$$

$$\therefore\ \Pi_k(x-\theta_s) \equiv (x(x-2))^{\frac{1}{2}\tau_{2^s}(k)} \text{ mod. } 2^s.$$

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And if $\frac{k}{a}$ be not equal to unity, then $\frac{1}{2}\tau_2(k)$ will be divisible by 2^{q-1} when $q = 2$. Then, since $[x(x-2)]^{2^{q-1}} \equiv x^{2^q} \bmod. 2^q$, it follows that

$$\Pi_s(x-\theta_s) \equiv (x)^{\tau_2 k} \bmod. 2^q, \text{ as before.}$$

But if $\frac{k}{a} = 1$ and $q = 2$, then $\frac{\tau_2(k)}{2^{q-1}}$ is odd, and we have, by Theorem II. as before,

$$\Pi_q(x-\theta_s) \equiv [x(x-2)]^{2^{q-1}} \equiv x^{2^{q-1}}(x^2 + 2^{q-1}x + 2^{q-1}) \bmod. 2^q,$$

where the last term in the parenthesis is present or absent according as $z > 2$ or $z = 2$.

$$\therefore \Pi_s(x-\theta_s) \equiv [x^{2^{q-1}}(x^2 + 2^{q-1}x + 2^{q-1})]^{\frac{\tau_2 k}{2^{q-1}}} \bmod. 2^q.$$

Now, $(x^2 + 2^{q-1}x + 2^{q-1})^n \equiv (x^2)^n + n(x^2)^{n-1}(2^{q-1}x) + (x^2)^{n-1}(2^{q-1})$ mod. 2^q which, when n is odd, becomes

$$\equiv x^{2n} + 2^{q-1}x^{2n-1} + 2^{q-1}x^{2n-2} \equiv x^{2n-2}(x^2 + 2^{q-1}x + 2^{q-1}) \bmod. 2^q.$$

Then, since $\frac{\tau_2 k}{2^{q-1}}$ is odd, we have for $z > 2$,

$$\Pi_s(x-\theta_s) \equiv x^{2^q 2^{q-1}-2}(x^2 + 2^{q-1}x + 2^{q-1})\, x^{2n-2} \bmod. 2^q,$$

where $n = \frac{\tau_2 k}{2^{q-1}}$. Now, since $\frac{k}{2^q}$ is odd, we have $\frac{1}{2}k = 2^{q-1}(2\lambda + 1)$. Then $2^{q-1} \equiv \frac{1}{2}k \bmod. 2^q$.

$$\therefore \Pi_s(x-\theta_s) \equiv x^{\tau_2 k - 2}\left(x^2 + \frac{1}{2}kx + \frac{1}{2}k\right) \bmod. 2^q,$$

which is exception (2), second part. In exactly the same way we get when $z = 2$,

$$\Pi_s(x-\theta_s) \equiv x^{\tau_2 k - 2}\left(x^2 + \frac{1}{2}kx\right) \bmod. 2^q,$$

which is exception (2), first part.

Having shown, now, that the formula of the theorem holds good with respect to any component of the modulus, the theorem is proved.

In the expansion of $R_a(x^{a-1}-1)^{\tau_2(k)}$ the coefficient of x^r is

$$\equiv (-)^{\frac{r(k)-r}{a-1}} R_a C_{\frac{r}{a-1}}^{\tau_2(k)} \text{ or } = 0,$$

according as r is or is not divisible by $a-1$, where $C_{\frac{r}{a-1}}^{\tau_2(k)}$ is a binomial coeffi-

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cient. For, if r contain $a-1$, then $(-)^{\gamma_a(k)-\frac{r}{a-1}} = (-)^{\frac{\gamma_a(k)-r}{a-1}}$. Therefore, putting $\tau_s(k) - r = m$, the preceding theorem may be stated as follows:

Theorem IV. If $k = a^\alpha b^\beta \ldots g^\gamma h^\varepsilon \ldots q^\sigma$, $s = h \ldots q$, and $P_m(\theta_s)$ denote $\Sigma\theta'_s\theta''_s \ldots \theta_s^{(m)}$, where θ'_s, &c. are the s-totitives of k, then

$$P_m(\theta_s) \equiv \sum_{\omega=a}^{\omega=g} (-)^{\overline{\omega-1}} R_\omega C^{\gamma_{\omega\sigma}(k)}_{\frac{m}{\omega-1}} \text{ mod. } k,$$

the summation including only those terms for which $\frac{m}{\omega-1}$ is an integer; except (1) when $\frac{k}{\sigma} = 4$ or a higher power of 2, in which case

$$P_m(\theta_s) \equiv (-)^{\frac{m}{2}} R_{\frac{1}{2}} C^{\frac{1}{2}\gamma_2(k)}_{\frac{m}{2}} \text{ mod. } k,$$

and (2) when $\frac{k}{\sigma} = 1$ and one of the components of $k = 2^n$, in which case, if $n = 2$, then

$$P_1(\theta_s) \equiv \tfrac{1}{2} k, \text{ and } P_{1+\lambda} \equiv 0 \text{ mod. } k,$$

but if $n > 2$, then

$$P_1(\theta_s) \equiv P_2(\theta_s) \equiv \tfrac{1}{2} k, \text{ and } P_{2+\lambda} \equiv 0 \text{ mod. } k.$$

When $m = \tau_s(k)$, the formula becomes

$$P_{\tau_s(k)}(\theta_s) \equiv R_a + R_b + \ldots + R_g \equiv R_{ab\ldots g} = R_s \text{ mod. } k,$$

except when $\frac{k}{\sigma} = p^n$, $2p^n$, or 4, and $\frac{\sigma}{s}$ is at the same time an odd number, in which case $\tau_s(k) : p - 1$ is odd, and the formula becomes

$$P_{\tau_s(k)}(\theta_s) \equiv -R_s \text{ mod. } k.$$

This special case of the formula is the generalization of the Wilsonian theorem given in my former paper, for $P_{\tau_s(k)}(\theta_s) =$ the product of the s-totitives of k.

Example. Suppose $k = 60 = 2^2 . 3 . 5$, then those three roots of $x^3 \equiv x$ mod. 60 which I have denoted by $R_{\frac{1}{2}}$, $R_{\frac{1}{3}}$, $R_{\frac{1}{5}}$ are 45, 40, 36 respectively.

I. $s = 1$.

$$P_m(\theta_1) \equiv (-)^{\frac{m}{\frac{1}{2}-1}} R_{\frac{1}{2}} C^{\gamma_2(60)}_{\frac{m}{\frac{1}{2}-1}} + (-)^{\frac{m}{\frac{1}{3}-1}} R_{\frac{1}{3}} C^{\gamma_3(60)}_{\frac{m}{\frac{1}{3}-1}} + (-)^{\frac{m}{\frac{1}{5}-1}} R_{\frac{1}{5}} C^{\gamma_5(60)}_{\frac{m}{\frac{1}{5}-1}} \text{ mod. } 60.$$

Whence

$$P_1(\theta_1) \equiv -45 . 16 \equiv 0,$$

$$P_2(\theta_1) \equiv 45 . \frac{16.15}{1.2} - 40 . 8 \equiv -20,$$

$$P_3(\theta_1) \equiv -45 . \frac{16.15.14}{1.2.3} \equiv 0,$$

$$P_4(\theta_1) \equiv 45 . \frac{16.15.14.13}{1.2.3.4} + 40 . \frac{8.7}{1.2} - 36 . 4 \equiv 16,$$

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etc., to $P_{16}(\theta_1) \equiv R_2 + R_3 + R_4 \equiv 1$.

These relations, expressed by Theorem III, become

$$\Pi(x-\theta_1) \equiv R_2(x-1)^{\frac{m}{2}} + R_3(x^3-1)^{\frac{m}{3}} + R_4(x^4-1)^{\frac{m}{4}} \text{ mod. } 60.$$

or,

$$\Pi(x-\theta_1) \equiv 45(x-1)^{16} + 40(x^3-1)^8 + 36(x^4-1)^6 \text{ mod. } 60.$$

II. $s = 5$.

$$P_m(\theta_1) \equiv (-)^{\frac{m}{2}-1} R_2 C^{\frac{m}{2}, \frac{m}{2}}_{\frac{m}{2}-1} + (-)^{\frac{m}{3}-1} R_3 C^{\frac{m}{3}, \frac{m}{3}}_{\frac{m}{3}-1} \text{ mod. } 60.$$

$$P_1(\theta_1) \equiv -45.4 \equiv 0,$$

$$P_2(\theta_1) \equiv 45.\frac{4.3}{1.2} - 40.2 \equiv 10.$$

$$P_3(\theta_1) \equiv -45.\frac{4.3.2}{1.2.3} \equiv 0.$$

$$P_4(\theta_1) \equiv 45 + 40 \equiv 25 = R_1.$$

These relations, when expressed by Theorem III. become

$$\Pi(x-\theta_1) \equiv 45(x-1)^4 + 40(x^3-1)^8 + 36x^4 \text{ mod. } 60.$$

III. $s = 3$.

$$P_m(\theta_1) \equiv (-)^{\frac{m}{2}-1} R_2 C^{\frac{m}{2}, \frac{m}{2}}_{\frac{m}{2}-1} + (-)^{\frac{m}{3}-1} R_3 C^{\frac{m}{3}, \frac{m}{3}}_{\frac{m}{3}-1} \text{ mod. } 60.$$

$$P_1(\theta_1) \equiv -45.8 \equiv 0.$$

$$P_2(\theta_1) \equiv 45.\frac{8.7}{1.2} \equiv 0.$$

$$P_3(\theta_1) \equiv -45.\frac{8.7.6}{1.2.3} \equiv 0.$$

$$P_4(\theta_1) \equiv 45.\frac{8.7.6.5}{1.2.3.4} - 36.2 \equiv 18. \text{ etc., to}$$

$$P_9(\theta_1) \equiv 45 + 36 \equiv 21 = R_1; \text{ otherwise.}$$

$$\Pi(x-\theta_1) \equiv 45(x-1)^9 + 40x^9 + 36(x^4-1)^9 \text{ mod. } 60.$$

IV. $s = 2$.

$$P_m(\theta_1) \equiv (-)^{\frac{m}{2}-1} R_2 C^{\frac{m}{2}, \frac{m}{2}}_{\frac{m}{2}-1} + (-)^{\frac{m}{3}-1} R_3 C^{\frac{m}{3}, \frac{m}{3}}_{\frac{m}{3}-1} \text{ mod. } 60.$$

$$P_1(\theta_1) \equiv 0.$$

$$P_2(\theta_1) \equiv -40.\frac{8.7}{1.2} \equiv 20.$$

$$P_3(\theta_1) \equiv 0.$$

$$P_4(\theta_1) \equiv 40.\frac{8.7.6.5}{1.2.3.4} - 36.4 \equiv 16, \text{ etc., to}$$

$$P_8(\theta_1) \equiv 40 + 36 \equiv 16 = R_1.$$

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V. $s = 2.3.$

$$P_m(\theta_{2.3}) \equiv (-)^{\frac{m}{3-1}} R_{\frac{k}{\sigma}} C_{\frac{m}{3-1}}^{r_{2.3}.\phi(60)} \text{ mod. } 60,$$
$$P_1(\theta_{2.3}) \equiv P_2 \equiv P_3 \equiv 0,$$
$$P_4(\theta_{2.3}) \equiv -36.2 \equiv -12,$$
$$P_5 \equiv P_6 \equiv P_7 \equiv 0,$$
$$P_8(\theta_{2.3}) \equiv 36 = R_{2.3}.$$

VI. $s = 3.5.$

This is a case of exception (1), since $\frac{k}{\sigma} = \frac{60}{3.5} = 4.$

$$\therefore P_m(\theta_{3.5}) \equiv (-)^{\frac{m}{2}} R_2 C_{\frac{m}{2}}^{2^2 r_{3.5}.\phi(60)} \text{ mod. } 60,$$
$$P_1 \equiv 0,$$
$$P_2 \equiv -45 = -R_{3.5}.$$

VII. $s = 5.2.$

$$P_m(\theta_{5.2}) \equiv (-)^{\frac{m}{2^2-1}} R_{\frac{k}{\sigma}} C_{\frac{m}{2^2-1}}^{r_{5.2}.\phi(60)} \text{ mod. } 60,$$
$$P_1 \equiv P_2 \equiv 0,$$
$$P_3(\theta_{5.2}) \equiv -40.2 = -20,$$
$$P_4(\theta_{5.2}) \equiv 40.\frac{2.1}{1.2} = R_{5.2}.$$

VIII. $s = 2.3.5.$

This is a case of exception (2), since $\frac{k}{\sigma} = \frac{60}{2^2.3.5} = 1$, and 60 contains 4.

$$\therefore P_1(\theta_{2.3.5}) \equiv \tfrac{1}{2}(60), \text{ and } P_2 \equiv 0 = R_{2.3.5}.$$

The only two numbers included here are

$$0 \text{ and } 30, \; P_1 = 0 + 30, \text{ and } P_2 = 0.30.$$

Theorem V. If $k = a^t b^u \ldots q^s$, and $\Pi_k(x-\theta)$ denote the continued product, $x(x-1)(x-2)\ldots(x-k-1)$, then

$$\Pi_k(x-\theta) \equiv R_a(x^a-x)^{\frac{k}{a}} + R_{\bar{b}}(x^b-x)^{\frac{k}{b}} + \ldots + R_{\bar{q}}(x^q-x)^{\frac{k}{q}} \text{ mod. } k;$$

except when one of the factors of k, as a, $= 2$, and $t > 1$, in which case

$$\Pi_k(x-\theta) \equiv R_{\bar{2}}[(x^2-x)^2 - 2(x^2-x)]^{\frac{k}{2}} + R_b(x^b-x)^{\frac{k}{b}} + \ldots + R_{\bar{q}}(x^q-x)^{\frac{k}{q}} \text{ mod. } k.$$

To prove this theorem we have only to consider one component of the modulus, as a^t. Since R_b, $R_{\bar{c}}, \ldots R_{\bar{q}}$ each contain a^t, and $R_{\bar{a}} \equiv 1$ mod. a^t, the congruence to be proved reduces to $\Pi_k(x-\theta) \equiv (x^a-x)^{\frac{k}{a}}$ mod. a^t. Now it is

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[illegible]

[illegible]

[illegible]

forms $x^a + \lambda_1 x^{a-1} + \lambda_2 x^{a-2} +$ &c., $x^b + \mu_1 x^{b-1} + \mu_2 x^{b-2} +$ &c., &c. respectively. It is well known that K can be so represented in only one way.

A function, $\phi(x)$, is said to contain another function, $f(x)$, *with respect to* p, when $\phi(x) = f(x)f_1(x) + pf_2(x)$. In the following the words *with respect to* p are always to be understood when the word *contain* is used with reference to functions, and when one function is said to be prime to another it is to be understood that they have no common factor *with respect to* p.

Let the number of incongruous (mod. p) functions of a less degree than that of K and prime to K be called the prime totient of K, and let it be denoted by $\tau_1(K)$ after the analogy of Professor Sylvester's notation and nomenclature in the case of integers. Likewise let the functions themselves be called the prime totitives of K. In the same way let the number of those which contain A but no other prime factor of K be called the A-totient of K, and let it be denoted by $\tau_A(K)$; and let the functions themselves be called the A-totitives of K. So on, for $\tau_{AB}(K)$, $\tau_{ABC}(K)$, &c. There are plainly 2^i different classes of totitives of K, if i denote the number of the unequal prime factors of K. A means of finding the value of the different totients of K will be furnished by the following:

Lemma. There are p^{n-m} *incongruous (mod.* p*) functions of* x*, degree* $< n$*, which contain a given function* $\phi(x)$ *of form* $x^m + \lambda_1 x^{m-1} + \lambda_2 x^{m-2} + \ldots + \lambda_m$.

For let $\psi(x) = \alpha x^{n-1} + \beta x^{n-2} +$ &c., where α, β, &c. are variable coefficients. Dividing $\psi(x)$ by $\phi(x)$, we get a remainder of degree $m-1$. In order that there may be an exact division, each of the coefficients of the remainder must be equal to zero. We thus have m equations, which, as the process of division shows, are linear in the n quantities, α, β, &c. We may give arbitrary values to $n-m$ of these quantities, and considering the system of equations as a system of congruences mod. p, we may evidently satisfy the system in p^{n-m} different ways. Hence the *lemma* is proved.

Suppose, now, that $K = A^a B^b C^c$. We easily find, by means of the preceding lemma, and by use of the process employed to find the totients of an integer, that

$$\begin{aligned}
\tau_1(K) &= p^{(a-1)a} p^{(a-1)b} p^{(a-1)c} (p^a - 1)(p^b - 1)(p^c - 1), \\
\tau_A(K) &= \quad " \qquad\quad (p^b - 1)(p^c - 1), \\
\tau_{AB}(K) &= \quad " \qquad\qquad (p^c - 1), \text{ &c.}
\end{aligned}$$

The analogy between these numbers and the totients of an integer is at once apparent, viz: if an integer $k = a^a b^b c^c$ where a, b, c are prime numbers, the totients of K are derived from the totients of k by substituting in the latter

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p^a for a, p^b for b, &c., where, however, a, b, c, the degrees of A, B, C, are not prime numbers, but any integers.

It is proposed, in what follows, to show briefly that certain theorems of my former paper, as well as those of the preceding section, have their analogues in the theory of functions (mod. p, K).

Let us first consider the properties of the roots of $X^\lambda \equiv X \pmod{p, K}$, where $K = A^\alpha B^\beta \ldots G^\gamma H^\varepsilon \ldots Q^\varphi$. Let $s = H \ldots Q$, and $\sigma = H^\varepsilon \ldots Q^\varphi$. We evidently have $X \equiv 0 \pmod{p, \sigma}$, and $X \equiv 1 \left(\mathrm{mod.}\ p, \frac{K}{\sigma}\right)$, and thence $\lambda\sigma - \mu\frac{K}{\sigma} \equiv 1 \pmod{p}$. Since σ and $\frac{K}{\sigma}$ have no common factor with respect to p, this congruence gives one, and only one, value of λ. (See Serret, *Cours d'Alg. Sup.*, § 341), and consequently one, and only one, value of X for the two preceding congruences. This value contains σ. Call it R_s. It is evident now that there are twice as many roots of $X^\lambda \equiv X \pmod{p, K}$ as there are ways of separating K into two factors prime to one another, viz: 2^i, and that one of them belongs to each of the 2^i classes of the totitives of K, where i is the number of the unequal prime factors in K. It is at once evident that these roots or repetents of K have the same properties as the integer roots of $x^\lambda \equiv x \pmod{k}$. For convenience, I restate some of them:

(1). $R_s R_{s'} \equiv R_{ss'} \pmod{p, K}$, where s and s' are prime to each other.

(2). The sum of any given number of the repetents of K is congruous (mod. p, K) to the sum of the same number of any others of them, provided only that the product of the subscripts is the same for each sum.

(3). If s denote the product of all the unequal prime factors of K *not* contained in s, then

$$R_s R_{s'} \equiv 0 \pmod{p, K},$$

(4). $R_s + R_{s'} + \ldots + R_{s\overline{s'}} \equiv R_{s\overline{s'\ldots s'}} \pmod{p, K}$.

(5). If $A', B', \ldots G'$ be prime totitives of $A^\alpha, B^\beta, \ldots G^\gamma$, respectively, and $H', \ldots Q'$ are multiples of $H, I, \ldots Q$, respectively, then the residue (mod. p, K) of the function, $A'R_A + BR_B + \ldots + QR_Q$ is an s-totitive of K.

The analogue of Fermat's extended theorem is $X_s^{\varphi(K)} \equiv R_s \pmod{p, K}$, where X_s is an s-totitive of K.

If $K = A^\alpha$, it is proved, in the ordinary way, that

$$X_1^{\varphi(A^\alpha)} \equiv 1 \pmod{p, K},$$

and it is, of course, obvious that

$$X_A^{\varphi(A^\alpha)} \equiv 0 \pmod{p, K}.$$

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Hence the theorem is true for $K = A^t$, since $R_1 = 1$ and $R_A = 0 \pmod{p, K}$. Then since [see (5)]

$$X_s \equiv A^t R_A + B^t R_B + \ldots + Q^t R_Q \pmod{p, K},$$

we have, by raising both sides to power $\tau_s(K)$, inasmuch as $\tau_s(K)$ contains $\tau_1(A^t), \ldots \tau_1(G^t)$,

$$X_s^{\tau_s(K)} \equiv R_A + R_B + \ldots + R_Q \equiv R_{AB\ldots Q} = R_s \pmod{p, K};$$

and the general theorem is proved.

Let it be required now to find the residues (mod. p, K) of the symmetric functions $\Sigma\Theta_s'$, $\Sigma\Theta_s'\Theta_s''$, &c., where Θ_s', Θ_s'', &c. are the s-totitives of K, or, in other words, to find the residue of the function $\Pi_K(X - \Theta_s)$, in analogy with the results of the preceding section. First, let us prove that $\Pi_{A^t}(X - \Theta_1) \equiv [\Pi_{A^{t-1}}(X - \Theta_1)]^{p^n} \pmod{p, A^t}$. The method of proof is precisely that of last section. Let α, β, γ, &c. be the prime totitives of A^{t-1}; then those of A^t will be given by $\alpha + \lambda A^{t-1}$, $\beta + \lambda A^t$, &c. where λ is any one of the p^n incongruous (mod. p) functions of n less degree than that of A. But

$$\Pi(X - \alpha + \lambda A^{t-1}) \equiv X^{p^n} - (C_1^{p^n}\alpha + \Omega A^{t-1})X^{p^n-1} + (C_2^{p^n}\alpha^2 + C_1^{p^n}\Omega A^{t-1}\alpha)X^{p^n-2} - (C_3^{p^n}\alpha^3 + C_2^{p^n-1}\Omega A^{t-1}\alpha^2)X^{p^n-3} + \&c. \pmod{p, A^t}$$

just as before, where Ω here equals the sum of the p^n incongruous (mod. p) functions of n less degree than that of A. But we evidently have $\Omega \equiv 0 \bmod p$.

$$\therefore \Pi(X - \alpha + \lambda A^{t-1}) \equiv (X - \alpha)^{p^n}, \pmod{p, A^t}.$$
$$\therefore \Pi_A(X - \Theta_1) \equiv [(X - \alpha)(X - \beta) \ldots]^{p^n}, \pmod{p, A^t}.$$
$$\therefore \Pi_{A^t}(X - \Theta_1) \equiv [\Pi_{A^{t-1}}(X - \Theta_1)]^{p^n}, \pmod{p, A^t}.$$

Now we know (*Serret*, § 345, *et seq.*) that

$$\Pi_A(X - \Theta_1) \equiv X^{p^n-1} - 1, \pmod{p, A},$$
$$\therefore \Pi_{A^t}(X - \Theta_1) \equiv (X^{p^n-1} - 1)^{p^{n(t-1)}}, \pmod{p, A^t},$$
$$\therefore \Pi_{A^t}(X - \Theta_1) \equiv (X^{p^n-1} - 1)^{p^{n(t-1)}}, \pmod{p, A^t}.$$

In the same way, we evidently get

$$\Pi_{A^t}(X - \Theta_A) \equiv (X)^{p^{n(t-1)}}, \pmod{p, A^t}.$$

In general we have the following

Theorem. If $K = A^t B^m \ldots G^u H^m \ldots Q^r$, where A, B, &c. are different irreducible (mod. p) functions of x, of degrees, a, b, &c. and if $S = HI \ldots Q$, and Θ_s', Θ_s'', &c. be the S-totitives of K, then

$$\Pi_K(X - \Theta_R) \equiv R_A(X^{p^{an}-1} - 1)^{\tau_{AR}(K)} + \ldots + R_Q(X^{p^{rn}-1} - 1)^{\tau_{RQ}(K)} + R_R X^{\tau_R(K)}, \pmod{p, K}.$$

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There are no exceptions to this formula as in the case of the corresponding formula for integers, for the unique prime number, 2, has no analogue in this theory of functions. The proof of the theorem is so nearly the same as that of the one for integers that it does not seem worth while to repeat it here. It is simply a substitution of μ^a for a, μ^b for b, &c. and (mod. μ, K) for mod. k in the proof of Theorem III in the last section.

If $P_m(\Theta_s)$ denote $\Sigma\Theta_s^{\alpha}\Theta_s^{\beta}\ldots\Theta_s^{\mu}$, we have as another form of the preceding theorem, analogous to Theorem IV of the last section,

$$P_m(\Theta_s) \equiv \sum_{\Omega=A}^{\Omega=\Theta} (-)^{\tau\Omega} R_\Omega C_{\frac{m}{\tau\Omega}}^{\frac{\tau_s K}{\tau\Omega}}, \text{ mod. } (\mu, K),$$

where the process of summation includes only those terms for which $\frac{m}{\tau(\Omega)}$, *i. e.*, $\frac{m}{\mu^n - 1}$ = an integer.

When $m = \tau_s(K)$, the formula becomes

$$P_{\tau_s K} \equiv R_A + R_B + \ldots + R_\Theta \equiv R_{AB\ldots\Theta} = R_\sigma,$$

except when $\frac{K}{\sigma}$ = a power of an irreducible function, as A', and μ is not 2, in which case $\frac{\tau_s(K)}{\tau(A)}$, *i. e.* $\frac{\tau_s(K)}{\mu^n - 1}$, is odd, and we have

$$P_{\tau_s K} \equiv -R_A = -R_B, \text{ (mod. } \mu, K).$$

Since $P_{\tau_s K}$ = the product of the s-totitives of K, this special case of the above theorem constitutes the analogue of the generalized Wilsonian theorem.

It is easy to see that Theorem V of last section also has its analogue here, viz: If $\Pi_x(X - \Theta)$ denote the continued product $(X - \Theta')(X - \Theta'')\ldots$ where Θ', Θ'', &c. are the whole set of the $x = \mu^{a+b+\ldots+q}$ incongruous (mod. μ, K) functions of x from 0 up to K, then

$$\Pi_x(X - \Theta) \equiv R_A(X^{\mu^a} - X)^{\mu^b} + \ldots + R_Q(X^{\mu^q} - X)^{\mu^p}, \text{ [mod. } \mu, K],$$

or

$$P_m(\Theta) \equiv (-)^{\mu^m - 1} R_A C_{\frac{m}{\mu^n - 1}}^{\frac{x}{\mu^n - 1}} + \ldots + (-)^{\frac{m}{\mu^n - 1}} R_Q C_{\frac{m}{\mu^n - 1}}^{\mu^q}, \text{ (mod. } \mu, K).$$

BALTIMORE, 14 *April*, 1881.

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Note on the Frequency of Use of the Different Digits in Natural Numbers.

By Simon Newcomb.

That the ten digits do not occur with equal frequency must be evident to any one making much use of logarithmic tables, and noticing how much faster the first pages wear out than the last ones. The first significant figure is oftener 1 than any other digit, and the frequency diminishes up to 9. The question naturally arises whether the reverse would be true of logarithms. That is, in a table of anti-logarithms, would the last part be more used than the first, or would every part be used equally? The law of frequency in the one case may be deduced from that in the other. The question we have to consider is, what is the probability that if a natural number be taken at random its first significant digit will be n, its second n', etc.

As natural numbers occur in nature, they are to be considered as the ratios of quantities. Therefore, instead of selecting a number at random, we must select two numbers, and inquire what is the probability that the first significant digit of their ratio is the digit n. To solve the problem we may form an indefinite number of such ratios, taken independently; and then must make the same inquiry respecting their quotients, and continue the process so as to find the limit towards which the probability approaches.

Let us suppose the numbers with which we commence to be arranged in periods according to the number of their digits, or, which is the same thing, according to the characteristics of their logarithms on the scale of which the basis is i, (i being 10 in the common system). Then, if two numbers are i^{c+s} and $i^{c'+s'}$, c and c' being integers, the significant figures of the ratio will be independent of c and c', since changing these integers will only change the decimal point. We may, therefore, take both numerator and denominator of the ratio out of the same period.

Moreover, since both numerator and denominator are formed by the same process, we may suppose the law of distribution of the numbers from which they are selected to be the same. Our problem is thus reduced to the following:

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We have a series of numbers between 1 and i, represented by fractional powers of i, say i^s, the distribution of the exponents s, and therefore of the numbers, being according to any arbitrary law. Since these exponents are formed by casting off all the integers from a series of numbers, we may suppose them arranged around a circle according to some law. Then, if we select 2^n exponents at random and call them s', s'', s''', etc., the final ratio, obtained in the manner we have described, will be

$$i^{s'-s''+s'''-s''''+\text{ etc.}}$$

The question is, what is the probability that the positive fractional portion of $s' - s'' + s''' - s''''$ + etc., will be contained between the limits s and $s + ds$. It is evident that, whatever be the original law of arrangement, the fractions will approach to an equal distribution around the circle as n is increased, or the required probability will be equal to ds. But, the fractional part of $s' - s'' + s'''$ — etc. is the mantissa of the logarithm of the limiting ratio. We thus reach the conclusion:

The law of probability of the occurrence of numbers is such that all mantissæ of their logarithms are equally probable.

In other words, every part of a table of anti-logarithms is entered with equal frequency. We thus find the required probabilities of occurrence in the case of the first two significant digits of a natural number to be:

Dig.	First Digit.	Second Digit.
0 . . .	. . .	0.1197
1 . . .	0.3010	0.1139
2 . . .	0.1761	0.1088
3 . . .	0.1249	0.1043
4 . . .	0.0969	0.1003
5 . . .	0.0792	0.0967
6 . . .	0.0669	0.0934
7 . . .	0.0580	0.0904
8 . . .	0.0512	0.0876
9 . . .	0.0458	0.0850

In the case of the third figure the probability will be nearly the same for each digit, and for the fourth and following ones the difference will be inappreciable.

It is curious to remark that this law would enable us to decide whether a large collection of independent numerical results were composed of natural numbers or logarithms.

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*Tables of the Generating Functions and Groundforms of the Binary Duodecimic, with some General Remarks, and Tables of the Irreducible Syzygies of certain Quantics.**

By J. J. Sylvester.

Generating Function for differentiants,

Denominator:

$$(1-a)(1-a^2)^2(1-a^3)(1-a^4)(1-a^5)(1-a^6)(1-a^7)(1-a^8)(1-a^9)(1-a^{10})(1-a^{11}).$$

Numerator:

$$1+4a^2+17a^3+49a^4+125a^5+285a^6+594a^7+1143a^8+2063a^9+3517a^{10}+5693a^{11}+8817a^{12}+13104a^{13}+18769a^{14}+25979a^{15}+34830a^{16}+45317a^{17}+57327a^{18}+70595a^{19}+84730a^{20}+99214a^{21}+113430a^{22}+126698a^{23}+138345a^{24}+147722a^{25}+154297a^{26}+157689a^{27}+157689a^{28}+154297a^{29}+147722a^{30}+138345a^{31}+126698a^{32}+113430a^{33}+99214a^{34}+84730a^{35}+70595a^{36}+57327a^{37}+45317a^{38}+34830a^{39}+25979a^{40}+18769a^{41}+13104a^{42}+8817a^{43}+5693a^{44}+3517a^{45}+2063a^{46}+1143a^{47}+594a^{48}+285a^{49}+125a^{50}+49a^{51}+17a^{52}+4a^{53}+a^{54}.$$

Generating Function for covariants, reduced form,

Denominator:

$$(1-a^2)(1-a^3)(1-a^4)(1-a^5)(1-a^6)(1-a^7)(1-a^8)(1-a^9)(1-a^{10})(1-a^{11})(1-ax^3)(1-ax^4)(1-ax^5)(1-ax^8)(1-ax^{10})(1-ax^{12}).$$

---

* The tables of the duodecimic have been calculated by Mr. F. Franklin in accordance with Professor Sylvester's second method (see this Journal, Vol. III, p. 146), in pursuance of a grant made by the British Association for the Advancement of Science. The corresponding tables for the binary quantics of the first ten orders are given in this Journal, Vol. II, p. 233; those for systems of quantics of the first four orders, taken two and two together, are given at page 293 of the same volume.

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Numerator :*

	x^0	x^1	x^2	x^3	x^4	x^5	x^6	x^7	x^8	x^9	x^{10}	x^{11}	x^{12}	x^{13}	x^{14}	x^{15}	x^{16}	x^{17}	x^{18}	x^{19}	x^{20}	x^{21}	x^{22}	x^{23}	x^{24}	x^{25}	x^{26}	x^{27}	x^{28}	x^{29}	x^{30}
a^0	1																													
a^1		1	1	1	1	1																								
a^2			1	1	2	2	3	2	2	1	1																			
a^3			1		1	1	1	2	3	3	3	3	2	1	1															
a^4	1		3	1	3		1			1	1	2	2	3	2	2	1	1												
a^5	1	1	4	2	2	1	2	2	3	2	2		1		1	1	1	1	1	1										
a^6	3	3	7	4	4		1	2	3			3	1	2	1	1														1
a^7	4	7	10	7	4	1	6	7	8	4	3	1	1	1		1	1	1												
a^8	7	12	17	10	6	2	11	13	12	5	2	5	3	6	2	1				1										
a^9	9	23	25	18	7	6	21	24	22	10	3	7	7	8	2	1	1	2		1										
a^{10}	17	36	39	25	5	15	39	45	37	16	1	16	16	15	5	1	2	3			1	1								
a^{11}	21	56	53	32	1	32	67	72	54	19	9	31	34	24	9	1	4	7	2	1	1									
a^{12}	36	81	76	44	7	52	100	108	72	17	24	56	56	35	11	5	14	13	4			3								
a^{13}	45	112	97	51	27	93	154	162	101	21	45	85	87	47	11	14	24	22	6	3	4									
a^{14}	65	151	133	63	45	134	216	218	120	3	90	143	136	69	15	22	40	32	8	7	7									
a^{15}	81	199	163	66	83	206	309	303	137	5	170	199	187	83	4	48	66	51	14	13	9									
a^{16}	110	251	206	69	134	282	404	386	173	32	226	261	237	114		69	97	68	16	24	17									
a^{17}	131	309	241	70	188	369	532	489	196	97	323	403	345	127	29	120	146	100	23	37	21									
a^{18}	168	379	288	51	253	495	653	580	198	188	460	550	446	150	58	169	202	127	33	57	36									
a^{19}	193	433	318	22	347	636	808	692	196	274	604	691	539	149	116	231	274	168	26	83	45									
a^{20}	232	493	359	6	436	759	939	770	153	421	797	863	635	160	176	329	352	204	19	115	65									
a^{21}	256	551	377	34	546	912	1093	861	119	534	989	1043	742	128	277	448	450	254	18	154	81									
a^{22}	293	598	402	97	648	1035	1209	969	85	646	1201	1252	844	110	372	553	543	292	1	201	110									
a^{23}	307	638	402	161	762	1174	1335	956	43	814	1402	1410	907	45	510	697	654	343	14	251	131									
a^{24}	336	667	407	210	852	1266	1404	948	168	1131	1619	1594	972	14	637	821	752	375	44	308	168									
a^{25}	339	679	381	280	953	1371	1480	944	274	1296	1791	1706	983	119	800	972	835	417	69	369	193									
a^{26}	351	678	367	326	1012	1465	1477	887	439	1508	1972	1836	997	209	954	1096	907	434	114	430	232									
a^{27}	339	664	323	382	1079	1446	1479	810	542	1632	2069	1860	997	351	1100	1225	1017	457	148	490	256									
a^{28}	336	635	291	410	1096	1414	1410	692	688	1782	2164	1900	983	453	1211	1301	1056	446	203	547	293									
a^{29}	307	595	239	445	1093	1360	1342	595	784	1837	2172	1837	784	595	1342	1360	1093	445	239	595	307									

* In the tabulated numerators, the *minus* sign is placed over the number which it affects.

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Numerator—(*Continued*):

	x^0	x^2	x^4	x^6	x^8	x^{10}	x^{12}	x^{14}	x^{16}	x^{18}	x^{20}	x^{22}	x^{24}	x^{26}	x^{28}	x^{30}	x^{32}	x^{34}	x^{36}	x^{38}	x^{40}
a^{30}	293	547	303	446	1056	1301	1211	453	893	1900	2164	1782	688	692	1410	1418	1086	410	291	655	336
a^{31}	256	490	148	457	1017	1225	1100	351	937	1860	2069	1632	542	810	1479	1446	1070	382	328	664	339
a^{32}	232	430	114	434	937	1086	934	269	997	1836	1972	1508	430	867	1477	1405	1012	326	367	678	351
a^{33}	193	369	69	417	855	972	800	119	983	1706	1791	1296	274	944	1480	1371	953	280	381	679	339
a^{34}	168	308	44	375	752	821	637	14	972	1594	1619	1131	168	948	1404	1266	852	210	407	667	336
a^{35}	131	251	14	343	654	697	510	45	907	1410	1402	914	43	956	1335	1174	762	161	402	638	307
a^{36}	110	201	1	292	543	553	372	110	844	1252	1201	746	35	909	1269	1035	648	97	402	598	293
a^{37}	81	154	18	254	450	448	277	128	742	1045	980	554	119	861	1093	912	546	54	377	551	256
a^{38}	65	115	19	204	352	329	176	160	633	883	797	421	153	770	989	759	436	6	359	493	232
a^{39}	45	83	26	168	274	251	116	149	539	691	604	274	196	692	808	636	347	22	318	433	196
a^{40}	36	57	23	127	202	169	58	150	446	550	460	188	193	580	653	495	253	51	288	370	168
a^{41}	21	37	23	100	146	120	29	127	345	403	323	97	196	489	532	389	188	59	241	309	131
a^{42}	17	24	16	68	97	69		114	267	301	226	53	173	386	404	282	124	69	206	251	110
a^{43}	9	13	14	51	66	48	4	83	187	199	139	5	157	303	309	206	83	66	168	199	81
a^{44}	7	7	8	32	40	22	15	69	136	143	90	3	120	218	216	134	45	63	133	151	65
a^{45}	4	3	6	22	24	14	11	47	87	85	45	21	101	162	158	93	27	51	97	112	45
a^{46}	3		4	13	14	5	11	35	56	56	24	17	72	108	100	52	7	44	76	81	36
a^{47}	1	1	2	7	6	1	9	24	34	31	9	19	54	72	67	32	1	32	53	56	21
a^{48}	1	1		3	2	1	5	15	16	16	1	16	37	45	39	15	5	25	39	36	17
a^{49}		1		2	1	1	2	8	7	7	3	10	22	24	21	6	7	18	25	23	9
a^{50}			1			1	2	6	3	5	2	5	12	13	11	2	6	10	17	12	7
a^{51}				1	1	1		1	1	1	3	4	8	7	6	1	4	7	10	7	4
a^{52}	1					1	1	3	1	3			3	2	1		4	4	7	3	3
a^{53}		1	1	1	1	1	1		1		2	2	3	2	2	1	2	2	4	1	1
a^{54}				1	1	2	2	3	2	2	1	1			1		3	1	3		1
a^{55}							1	1	2	3	3	3	3	2	1	1	1		1		
a^{56}											1	1	2	2	3	2	2	1	1		
a^{57}																1	1	1	1	1	
a^{58}																					1

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Generating Function for cocovariants, representative form.

Denominator:

$$(1-a^3)(1-a^4)(1-a^4)(1-a^5)(1-a^6)(1-a^7)(1-a^7)(1-a^8)(1-a^{10})$$
$$(1-a^{11})(1-a^3x^4)(1-a^3x^5)(1-a^3x^{12})(1-a^4x^{14})(1-a^4x^{20})(1-a^{23}).$$

Numerator:

	x^0	x^1	x^2	x^3	x^4	x^5	x^6	x^7	x^8	x^9	x^{10}	x^{11}	x^{12}	x^{13}	x^{14}	x^{15}	x^{16}	x^{17}	x^{18}	x^{19}	x^{20}	x^{21}	x^{22}	x^{23}	x^{24}
a^0	1																							
a^2					1	1	2	1	2	2	1	2	1	1	1	1		1						
a^4	1			3	2	4	3	4	4	3	4	2	3	1	2	1	1		1					
a^6	1	2	5	6	7	8	6	9	5	6	3	4	1	1			1		2					
a^8	3	4	9	11	13	15	13	15	9	11	5	6	2	1			1		3					
a^{10}	4	10	16	21	23	27	23	24	18	15	10	6	3	2	1	5			4					
a^{12}	7	16	28	34	40	46	40	37	27	22	12	6		5	5	10	5	7						
a^{14}	9	30	44	58	64	71	64	55	39	27	13	3	8	18	16	22	14	13						
a^{16}	17	45	71	89	99	110	97	77	51	29	5	15	30	40	39	42	30	23						
a^{18}	21	73	106	133	148	156	137	101	62	20	10	50	65	83	76	74	54	38						
a^{20}	36	102	153	191	208	218	187	123	61	1	53	102	129	146	136	120	89	59						
a^{22}	45	148	214	265	287	288	240	143	55	44	113	190	220	239	218	181	131	75						
a^{24}	65	196	290	353	377	378	299	152	21	114	218	309	352	363	327	258	178	89						
a^{26}	81	264	379	460	486	460	357	147	33	226	357	483	524	528	467	344	227	90						
a^{28}	110	332	486	577	601	558	408	118	129	376	558	694	750	725	627	439	266	68						
a^{30}	131	419	602	707	728	647	442	61	261	587	805	972	1018	960	810	529	286	12						
a^{32}	168	501	728	842	848	734	457	30	432	840	1122	1287	1330	1216	996	604	266	91						
a^{34}	193	601	856	979	970	800	443	160	677	1160	1476	1654	1664	1489	1171	644	194	265						
a^{36}	232	686	985	1106	1068	854	397	331	964	1516	1887	2038	2017	1751	1318	636	48	507						
a^{38}	256	783	1102	1223	1158	867	318	541	1279	1920	2310	2451	2356	1995	1422	556	171	842						
a^{40}	293	854	1209	1319	1207	865	209	785	1635	2332	2758	2831	2673	2183	1451	403	491	1259						
a^{42}	307	931	1293	1388	1241	814	54	1050	1963	2763	3171	3200	2930	2310	1408	151	893	1768						
a^{44}	336	974	1352	1430	1225	744	118	1330	2364	3155	3567	3490	3115	2352	1363	182	1393	2335						
a^{46}	339	1015	1384	1437	1192	631	310	1607	2691	3525	3876	3719	3294	2499	1532	614	1953	2967						
a^{48}	351	1017	1385	1409	1110	507	511	1867	2998	3812	4128	3934	3492	2644	1598	1105	2575	3605						
a^{50}	339	1015	1352	1353	1018	350	704	2095	3224	4033	4249	3960	3967	1963	301	1661	3199	4244						
a^{52}	336	974	1294	1267	887	203	883	2274	3389	4139	4281	3752	2839	1550	175	2223	3884	4823						
a^{54}	307	931	1210	1156	762	88	1032	2399	3452	4162	4183	3538	2518	1143	658	2788	4374	5329						
a^{56}	293	854	1105	1031	611	100	1146	2456	3446	4059	3998	3251	2127	692	1158	3290	4850	5697						
a^{58}	256	783	988	893	482	236	1219	2447	3333	3876	3701	2881	1690	226	1612	3730	5188	5942						

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Numerator—(*Continued*):

x^{28}	x^{29}	x^{30}	x^{31}	x^{32}	x^{33}	x^{34}	x^{35}	x^{36}	x^{37}	x^{38}	x^{39}	x^{40}	x^{41}	x^{42}	x^{43}	x^{44}	x^{45}	x^{46}	x^{47}	x^{48}	x^{49}	x^{50}	x^{51}	x^{52}	x^{53}	x^{54}	x^{55}	x^{56}	x^{57}	x^{58}	x^{59}	x^{60}	x^{61}	x^{62}	x^{63}	x^{64}	x^{65}	x^{66}	x^{67}	x^{68}	x^{69}	x^{70}	
																																											a^0
																																											a^3
																																											a^4
																																											a^5
													2		1			1																									a^6
													2		1			1																									a^7
													1		1			2			2			1			1																a^8
												2	2	1				2			1			1																			a^9
												7	4	3	2			3			1						1																a^{10}
												13	8	2	2	3	5	2	3	1							1															a^{11}
												22	6		10	7	11	6	7	2	1			1			1														1	a^{12}
												28	3	11	20	20	22	15	11	4	1			1	1	1																a^{13}
												32	15	31	45	40	43	29	18	7		1	5	2	3																	a^{14}
												18	46	75	85	78	73	51	27	9	1	5	9	7	4	1																a^{15}
												8	106	139	149	130	115	79	37	9	10	14	19	12	8	2															1	a^{16}
												73	199	247	237	209	169	116	46	2	23	31	34	24	13	4	1	2	1													a^{17}
												177	344	392	367	311	243	161	51	11	50	58	55	37	21	5	3	4	3													a^{18}
												348	540	602	526	445	326	206	48	43	90	100	88	63	28	7	8	10	4													a^{19}
												582	813	861	740	601	427	250	29	94	155	163	132	89	42	7	14	16	7													a^{20}
												906	1153	1192	980	780	525	279	12	179	244	250	195	132	51	5	27	30	9													a^{21}
												1298	1574	1564	1264	962	621	287	91	298	375	365	271	174	69	3	42	45	17													a^{22}
												1788	2048	1998	1553	1149	692	260	207	468	537	510	366	232	75	15	70	73	21													a^{23}
												2334	2558	2443	1862	1312	734	191	378	680	748	684	476	283	88	40	105	102	36													a^{24}
												2947	3140	2910	2135	1441	723	57	600	954	993	890	597	348	82	74	154	148	45													a^{25}
												3568	3714	3338	2388	1510	656	134	886	1269	1285	1116	730	394	78	123	216	196	65													a^{26}
												4201	4240	3733	2561	1511	513	399	1221	1639	1595	1360	860	444	48	189	293	264	81													a^{27}
												4772	4721	4029	2667	1422	296	723	1617	2029	1942	1605	967	466	14	272	383	332	110													a^{28}
												5285	5088	4239	2658	1250	2	1115	2036	2454	2276	1844	1098	480	53	370	490	419	131													a^{29}
												5665	5349	4301	2561	981	359	1538	2489	2858	2612	2062	1183	454	124	488	606	501	168													a^{30}
												5920	5442	4350	2331	634	780	2003	2925	3357	2995	2242	1237	417	283	615	731	601	193													a^{31}
												6003	5403	4343	2023	225	1231	2446	3347	3592	3161	2274	1251	330	340	753	860	686	233													

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Numerator—(*Continued*):

	x^0	x^1	x^2	x^3	x^4	x^5	x^6	x^7	x^8	x^9	x^{10}	x^{11}	x^{12}	x^{13}	x^{14}	x^{15}	x^{16}	x^{17}	x^{18}	x^{19}	x^{20}	x^{21}	x^{22}	x^{23}	x^{24}	x^{25}	x^{26}	x^{27}	x^{28}	x^{29}	x^{30}	x^{31}	x^{32}	x^{33}	x^{34}
a^{20}	232	686	860	753	340	330	1251	2374	3161	3592	3347	2446	1221	225	2023	4043	5408	6008																
a^{23}	198	601	731	615	283	417	1237	2342	2905	3257	2925	2068	780	634	2331	4250	5442	5920																
a^{24}	168	501	606	488	124	454	1183	2062	2612	2858	2449	1538	359	981	2561	4301	5349	5665																
a^{25}	131	419	490	370	53	480	1098	1844	2276	2454	2036	1115	2	1350	2658	4329	5088	5385																
a^{26}	110	332	383	272	14	466	987	1605	1942	2029	1617	733	298	1422	2667	4029	4721	4772																
a^{27}	81	264	293	189	48	444	860	1360	1596	1639	1221	399	513	1511	2561	3738	4340	4201																
a^{28}	65	196	216	123	78	394	730	1116	1285	1269	886	134	656	1510	2388	3338	3714	3568																
a^{29}	45	148	154	74	82	348	597	890	993	954	600	57	728	1441	2135	2910	3140	2947																
a^{30}	36	102	105	40	88	283	476	684	748	640	378	191	734	1312	1862	2443	2588	2334																
a^{31}	21	73	70	15	75	232	366	510	537	468	267	260	692	1149	1553	1998	2048	1788																
a^{32}	17	45	42	3	69	174	271	365	375	298	91	287	621	962	1264	1564	1574	1298																
a^{33}	9	30	27	5	51	132	193	250	244	179	12	279	525	780	980	1192	1152	906																
a^{34}	7	16	14	7	42	89	132	163	155	94	29	250	427	601	740	861	815	582																
a^{35}	4	10	8	7	28	63	88	100	90	43	48	206	326	445	526	602	540	348																
a^{36}	3	4	3	5	21	37	55	58	50	11	51	161	243	311	367	392	344	177																
a^{37}	1	2	1	4	13	24	34	31	23	2	46	116	169	209	237	247	199	73																
a^{38}	1			2	8	12	19	14	10	9	37	79	115	130	149	139	106	8																
a^{39}				1	4	7	9	5	1	9	27	51	72	78	85	75	46	18																
a^{40}					3	2	5	1		7	18	29	43	40	45	31	15	32																
a^{41}					1	1	1		1	4	11	15	22	20	20	11	3	28																
a^{42}	1				1		1		1	2	7	6	11	7	10		6	22																
a^{43}							1		1	3	2	5	3	2	2	2	8	13																
a^{44}				1		1		1			1		3		2	3	4	7																
a^{45}									1		1		2		1	2		2																
a^{46}							1		1		2		2		1		1																	
a^{47}													1		1		2																	
a^{48}													1																					
a^{49}																																		
a^{50}																																		
a^{51}																																		
a^{52}																																		
a^{53}																																		

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Numerator—(*Continued*):

x^{36}	x^{38}	x^{40}	x^{42}	x^{44}	x^{46}	x^{48}	x^{50}	x^{52}	x^{54}	x^{56}	x^{58}	x^{60}	x^{62}	x^{64}	x^{66}	x^{68}	x^{70}	
5942	3188	3730	1612	226	1690	2881	3701	3876	3383	2447	1219	226	482	893	988	783	256	α^{32}
5697	4850	3290	1158	692	2127	3251	3998	4059	3446	2456	1146	100	611	1031	1105	854	293	α^{33}
5329	4374	2788	638	1143	2518	3558	4183	4162	3452	2399	1032	88	762	1156	1210	981	307	α^{34}
4823	3824	2223	175	1550	2839	3752	4281	4139	3389	2274	883	208	887	1267	1294	974	306	α^{35}
4244	3199	1661	301	1893	3067	3860	4249	4033	3224	2095	704	350	1018	1353	1352	1015	339	α^{36}
3605	2575	1105	693	2144	3192	3834	4123	3812	2998	1867	511	507	1110	1409	1385	1017	351	α^{37}
2967	1953	614	1032	2299	3204	3719	3876	3525	2691	1607	310	631	1192	1437	1384	1015	339	α^{38}
2335	1393	182	1263	2352	3115	3490	3567	3155	2364	1330	118	744	1225	1430	1352	974	336	α^{39}
1768	893	151	1408	2310	2930	3200	3171	2763	1993	1050	54	814	1241	1388	1293	931	307	α^{40}
1259	491	403	1451	2183	2673	2831	2758	2332	1635	785	203	865	1207	1319	1209	854	293	α^{41}
842	171	556	1422	1995	2356	2451	2310	1920	1279	541	318	867	1158	1229	1102	783	256	α^{42}
507	48	636	1318	1751	2017	2038	1887	1516	964	331	397	854	1068	1106	985	686	232	α^{43}
265	194	644	1171	1489	1664	1654	1476	1160	677	160	443	800	970	979	856	601	193	α^{44}
91	266	604	996	1216	1330	1287	1122	840	452	30	457	734	848	842	728	501	168	α^{45}
12	286	529	810	960	1018	972	805	587	261	61	442	647	728	707	602	419	131	α^{46}
68	266	439	627	735	750	694	558	376	129	118	408	558	601	577	486	332	110	α^{47}
90	227	344	467	528	524	483	357	226	83	147	357	460	486	460	379	264	81	α^{48}
89	178	258	327	363	352	309	218	114	21	152	299	373	377	353	290	196	65	α^{49}
73	131	181	218	239	220	190	113	44	55	143	240	288	287	265	214	148	45	α^{50}
59	89	120	136	146	129	102	53	1	61	123	187	218	208	191	153	102	36	α^{51}
38	54	74	76	83	65	50	10	20	62	101	137	156	148	133	106	73	21	α^{52}
23	30	42	39	40	30	15	5	29	51	77	97	110	99	89	71	45	17	α^{53}
13	14	22	16	18	8	3	13	27	39	55	64	71	64	58	44	30	9	α^{54}
7	5	10	5	5		6	12	22	27	37	40	46	40	34	28	16	7	α^{55}
4		3	1	2	3	6	10	15	18	24	26	27	23	21	16	10	4	α^{56}
3		1		1	2	6	5	11	9	15	13	15	13	11	9	4	3	α^{57}
2		1		1	1	4	3	6	5	9	6	8	7	6	5	2	1	α^{58}
1		1	1	1	2	1	3	2	4	3	4	4	3	4	2	3		α^{59}
			1		1	1	1	1	2	1	2	2	1	2	1	1		α^{60}
																	1	α^{62}

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Table of Groundforms

ORDER IN THE VARIABLES.

DEGREE IN THE COEFFICIENTS.	1	2	3	4	5	6	7	8	9	10	11	12	13	14
2	1		1		1		1		1		1			
3	1		1	1	2	1	2	1	2	1	1	1	1	
4	2		3	2	4	3	4	4	3	4	3	3	3	3
5	2	2	5	6	7	9	9	9	5	6	3	4	2	
6	4	4	9	11	12	14	14	12	8	5				
7	5	10	15	20	19	21	19	9						
8	7	14	24	29	31	31								
9	9	20	33	37	35									
10	14	30	47	46										
11	15	38	60											
12	19	56	7											
13	19	64												
14	12													

The total number of groundforms (counting in the absolute constant and the quantic itself) is 949.

The manuscript sheets containing the original calculations from which the preceding tables have been constructed (as is the case also with the calculations connected with all the similar tables which have appeared in this journal) are deposited in the iron safe of the Johns Hopkins University, Baltimore, where they can be seen and examined, or copied, by any one interested in the subject. From the manifold independent systematic tests* to which the work has been

* One of these tests depends upon the following property of the generating function, which has been overlooked by observation, and of which the significance is not yet known. On putting $a = 1$ in the numerator of the generating function, the coefficients of the various powers of x are integer multiples of the coefficient of x^0. Thus in the case of the duodecimic, the numerator of the reduced form becomes on putting $a = 1$,

$$1 + 2x^2 + x^3 - x^4 - 3x^5 - 4x^6 - 4x^7 - 2x^8 + 2x^{10} + 3x^{11} + 6x^{12} + 3x^{13} + 2x^{14} - 2x^{15} - 4x^{16} - 4x^{17} - 3x^{18} - x^{19} + x^{20} + 2x^{21} + x^{22}).$$

Thus the numerical divisibility of the result of putting $a = 1$ furnishes a test for the sums of the *columns*, while the algebraic divisibility of the result of putting $x = 1$ (see this Journal, Vol. III. p. 131) tests the sums of the *rows*; and the satisfaction of both tests makes the correctness of the result practically certain.

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subjected, Mr. Franklin estimates that the chance is far more than a million to one that the generating functions for the twelfthic as calculated do not contain a single numerical error. The highest order of any ground-covariant to the twelfthic it will be seen is 34, which is the superior limit of order given by M. Camille Jordan's formula for the ground-covariants to a system of an indefinite number of simultaneous binary forms of each of which the order is 12 or less: M. Jordan's "superior limit" in fact in this as in all the other calculated cases, being actually attained by one (and only one) ground-covariant to a single form.* It will also be noticed that for all orders of the primitive which have been calculated, viz., from 3 to 12 (with 11 omitted), the degree of the covariant of highest order is either 3 or 4. Looking at single quantics of the even orders 6, 8, 10, 12, it will be observed that the maximum order of their ground covariants for any degree (from and after the 4th degree) diminishes, or, to speak more strictly, never increases as the degree increases. As regards quantics of the odd orders 5, 7, 9, the same rule applies for the maximum order of their groundforms of even degrees; and in respect to their groundforms of odd degrees, the maximum order from and after the 3d degree diminishes or remains stationary as the degree increases. Also (alike for quantics of odd or even order) when (beginning with the 3d degree) in passing from an odd to the next even or from an even to the next odd degree of the groundforms, an increase in the maximum order takes place, it is only to the extent of a single unit. These facts, which constitute a sort of *law of shrinkage*, assume practical importance when the successive tables of groundforms are compared together, with a view to track the ground-differentiants, (or, in Mr. Cayley's language, the ground-seminvariants or *sources* of covariants) as the order of the primitive quantic is increased. Some of these ground-sources retain their irreducible character permanently, others only up to a particular limit of order in the primitive. The former may be regarded as the irreducible differentiants to a quantic of an infinite order: such for instance are all the differentiants of the second and third degree. But when we consider differentiants of the 4th degree this is no longer true. Thus we have the well-known example of the discrimi-

* It is also particularly noticeable that the number of the successively positive and negative blocks in the table follows the law observed in the inferior cases, viz. for Quantics of orders 3 and 4 there is a single block, for Quantics of orders 5 and 6 two blocks, for order 8 three blocks, and for orders 9 and 10 four blocks, there being five distinct blocks alternately positive and negative in the instance before us of the Quantic of order 12.

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[illegible] a, b, c, d, e, f, viz. $af - 4be + 3cd$, which is irreducible [illegible] the quantic [illegible] remains it is evidently a differential, but no longer a ground-differential being expressible under the form of the difference of two products of linear differentials viz. as

$$\begin{vmatrix} a & b & c \\ b & c & d \\ c & d & e \end{vmatrix}$$

Suppose a differential to be the source of a covariant of the degree j considered as belonging to the quantic $(a, \ldots, x)^i$; then it is easily seen that it will be the source of a covariant of the degree j, $j+\epsilon$ in respect to the quantic $(a, \ldots, x)^{i-\epsilon}$. We can therefore in many cases by a mere inspection of the twelve tables of groundforms eliminate one at least of the transient ground-differentials, i.e. wherever there are K groundforms of degree j, ϵ to a quantic of the order i, but only $K - \Delta$ of the degree j, $\epsilon - \lambda j$ to the quantic of the order $i - \lambda$, we know that at least Δ of the ϵ ones to the K groundforms, i.e. Δ ground-differentials of degree j and weight $\frac{\theta - \epsilon}{2}$ are only transiently irreducible. Thus, e.g. in the table of groundforms for the quintic exhibits a groundform of deg-order 4, 4, i.e. of deg-weight 4, 8; but the table of groundforms for the sextic contains no groundform of the same deg-weight, i.e. of deg-order 4, 8. Hence the differential of deg-weight 4, 8, although irreducible when regarded as a function of 6 letters may be a number of letters which actually appear in it, is reducible when regarded as a function potentially of 7 or more.

So again, for a like reason, the ground-differentials of 5 letters, of deg-orders in respect to the quintic 5, 1 and 5, 7, i.e. of deg-weights 5, 12, 5, 6, are only transiently irreducible; and what is very interesting it will be seen at a glance, and here the law of shrinkage makes its importance felt, that the twelve tables of all the groundforms to a quintic of a higher order than the five are only transitory or provisional, so to say, ground-differentials. So in like manner it will be recognized by comparing the tables of groundforms for the seventh and eighth, that of the 9 ground-sources of the degree 6 to the former only two can be permanent, viz. one of the weight $\frac{6.7-2}{2}$ and one of the weight $\frac{6.7-4}{2}$, i.e. of the deg-weights 6, 10 and 6, 12 respectively: all

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the others becoming resoluble when an additional letter is introduced into the quantic. Moreover, as the table for the eighthic contains no groundforms of deg-order 7 . 8, we see from the law of shrinkage that there can be no ground-source to the seventhic of a higher than the 6th degree which is permanently irreducible.*

A systematic weeding out of the transitory ground-sources from the published tables, which cannot in all cases for groundforms of earlier degrees be effected completely without an examination of a more searching kind than that illustrated by the above examples, must be reserved for a future occasion—after I shall have completed, as I hope soon to do, the study of a subject of higher interest and more pressing importance, which has for its object to determine not only the ground-forms so called, but also the ground-syzygants, the ground-counter-syzygants, etc., of quantics from their generating functions by a purely arithmetical process, which I believe to be already substantially in my possession.

As the first fruits of this method, I may state that the invariantive ground-syzygants (or, if the expression is preferred, fundamental syzygies) to the octavian quantic $(x, y)^8$ are 5 in number, and of the degrees 16, 17, 18, 19, 20 respectively in the coefficients. As regards the ground-syzygants (invariantive and covariantive) of the quintic, my method furnishes the same list as that given in Professor Cayley's Tenth Memoir on Quantics. Their deg-orders may be found as follows.

By the supernumerary ground-types understand the deg-orders of the ground-covariants exclusive of those represented by the factors which appear in the denominator of the representative generating function,† which are therefore $23 - 6$, *i. e.* 17 in number. Let these types be added each to itself and every other, thus giving rise to $\frac{17 \cdot 18}{2}$ types: out of these sums strike out the types

$$8.4 \quad 9.5 \quad 10.2 \quad 10.4 \quad 11.3 \quad 12.2 \quad 14.4 \quad 16.2$$

and replace them by

$$13.5 \quad 14.6 \quad 15.3 \quad 15.5 \quad 16.4 \quad 17.3 \quad 19.5 \quad 21.3$$

The 153 types thus formed, together with the types, 26 in number, furnished by the negative terms in the numerator to the generating function, (see this Journal,

* For the 6th degree it will at once be seen that there can be no permanent differentiant to the seventhic except one of the 2d and one of the 4th order.

† In such denominator the number of factors for a Quantic of any odd order $2i-1$ is $3i-3$, and for any even order $2i$ is $3i-2$ (i in each case being supposed greater than unity).

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vol. II, p. 224) 179 in all, will be the deg-orders of the fundamental syzygants. Mr. Cayley founds this rule on his theory of the so-called Rota Generating Function, which essentially consists in what may be termed the Dialytic Presentation of the Representative G. F. for the Quintic—namely as a sum of 24 pairs, each pair containing one positive and one negative term of the numerator divided by the denominator, so selected for conjunction that the developed expression of each pair shall be seen to be omni-positive by an obvious dialytic process.

The method followed by the eminent author in finding out the fundamental *syzygants* does not appear (as far as I can make out, to be explicitly stated in his memoir. The dialytic form (supposing, as is probably the case, it always exists for *finite* representative generating functions) is not easy to arrive at: a serious additional obstacle to the use of the dialytic method would arise in the case where (as for the seventhic) the numerator of the representative form becomes an infinite series. The method I employ does not require the use of the dialytic method, nor even of the *representative* form of the G. F., although the practical process is much simplified by the use of the representative form when it has a finite numerator. The result I obtain for the fundamental syzygants of the sextic is as follows: Take the 19 supernumerary ground-types (see vol. II, p. 225) and add them each to each and to every other, as in the preceding case. Then strike out of the sums so formed the types of the deg-orders 6.4, 9.6, 8.4, 11.6, 10.4, 7.8, 8.6, 11.4, as well as one of the two sums 13.4 obtained from the addition of 5.2 and 8.2 or of 3.2 and 10.2 and replace the nine types so omitted by the eight types 12.8, 14.8, 13.6, 15.6, 10.10, 11.8, 14.6, 15.6. There will thus arise $19 \cdot \frac{20}{2} - 9 + 8$, or 189 types: to these adjoin the 29 types given by the negative terms in the numerator of the Rep. G. F.: the total number of types 189 + 29 or 218 so obtained will be the deg-orders of the complete system of fundamental syzygants to the sextic. The two types of the deg-order 6.6 which appear among the supernumerary types, it will of course be understood, are to be treated as distinct types in forming the binary sums. It is just barely possible (but I think very unlikely) that I may have committed some oversight in the table of replacement in the above calculation, and that the true number of ground-syzygies may be $19 \cdot \frac{18}{2} + 29$ or 219 instead of 218.*

* Nine binary sums of types are omitted, and are replaced by only eight other combinations. This is analogous to the loss of a unit in counting the irreducible syzygies to the invariants of an eighthic. The *supernumerary* invariants in this case are 3 in number; of degrees 8, 9, 10 respectively. Their binary combinations would give 6, but the true number of irreducible syzygies is only 5.

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I subjoin a brief *aperçu* of the general theory.

A generating function (whatever its subject-matter) developed in a series consists of facients and coefficients, where any facient is a product of a finite set of letters each raised to a certain power. The totality of the exponents expressing these powers may be termed the type of the facient. In the generating functions to be referred to hereinunder, the letters employed are just as many in number as there are quantics in the system to be considered: viz., one letter corresponds to each quantic.

A generating function proper (with reference to the present theory) is defined to be one that is or can be developed into a series of facients whose coefficients and whose types are omni-positive integers, and where each such numerical coefficient is the number of linearly independent invariants whose degrees in the coefficients of the several quantics of the system are identical with the indices of the corresponding letters in the facient to which that numerical coefficient is attached.* The type of the facient may be also styled the type of the connoted invariants. A binomial expression consisting of unity followed by a facient and separated from it by the negative sign may be termed a *generator*.†

A proper generating function to a system of quantics may always by known methods (see this Journal, vol. III, p. 133) be expressed by a fraction whose numerator is a finite series of facients with numerical coefficients and its denominator a finite product of generators.

It may also be expressed (according to a definite process), and in one way only, by a fraction whose numerator and denominator alike consist of a finite or infinite (except in a few trivial cases, an infinite) product of generators.‡

* I speak designedly (for greater facility of expression) of invariants only, which can be done for binary quantics without any loss of generality, inasmuch as covariants may be regarded as invariants of a given system of quantics with a linear quantic superadded.

† If a, b, c, . . . are facients, $1-a^\alpha b^\beta c^\gamma \ldots$ is a *generator*, and $\alpha, \beta, \gamma \ldots$ (taken in a definite order) is its *type*.

‡ For instance let G be the generating function proper to the invariants of an eighthic.

$$\text{Then } G = \frac{1+a^4+a^9+a^{10}+a^{13}}{(1-a^2)(1-a^3)(1-a^4)(1-a^5)(1-a^6)(1-a^7)(1-a^8)}$$
$$= [(1-a^2)(1-a^3)(1-a^4)(1-a^5)(1-a^6)(1-a^7)(1-a^8)(1-a^9)(1-a^{10})]^{-1}$$
$$\cdot\ (1-a^{14})(1-a^{17})(1-a^{18})(1-a^{19})(1-a^{20})$$
$$\cdot\ [(1-a^{23})(1-a^{25})(1-a^{27})(1-a^{28})(1-a^{29})]^{-1}$$
$$\cdot\ (1-a^{33})(1-a^{34})(1-a^{35})^2(1-a^{36})^2(1-a^{37})^2(1-a^{38})(1-a^{39})$$
$$\cdot\ [(1-a^{41})(1-a^{42})^2(1-a^{43})^2(1-a^{44})^2(1-a^{45})^2(1-a^{46})^2(1-a^{47})^2(1-a^{48})^2]^{-1}$$
$$\cdot\quad \cdot\quad \cdot\quad \cdot\quad \cdot\quad \cdot\quad \cdot\quad \cdot\quad \cdot\quad \cdot\quad \cdot\quad \cdot\quad \cdot\quad \cdot\quad \cdot\quad \cdot\quad \cdot\quad \cdot$$

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A finite system of generators is termed a generating-group, and the number of generators in such a system is termed the order of the generating-group.

The groups will be arranged in a series according to the number of generators which they contain, and the number of the group in the series will be termed the index of the group.

The groups of the first series, or those which contain only one generator, will be termed cyclical groups, and the generator of the group G will be denoted by G^1. The groups of the second series, or those which contain two generators, will be termed bicyclical groups, and the generators of the group G will be denoted by G^1, G^2. The groups of the third series, or those which contain three generators, will be termed tricyclical groups, and the generators of the group G will be denoted by G^1, G^2, G^3. And so on.

The groups of the n^{th} series will be termed n-cyclical groups, and the generators of the group G will be denoted by $G^1, G^2, G^3, \ldots G^n$.

Let $\Gamma_0, \Gamma_1, \Gamma_2, \ldots \Gamma_{n-1}$ be n groups of the n^{th} series of n-cyclical groups, and let the generators of the group Γ_0 be denoted by $G^1, G^2, G^3, \ldots G^n$, the generators of the group Γ_1 by $H^1, H^2, H^3, \ldots H^n$, and so on, the generators of the group Γ_{n-1} by $K^1, K^2, K^3, \ldots K^n$. Then the group Γ_0 will be said to be related to the group Γ_1 when the group Γ_1 may be made to represent a complete system of irreducible syzygies of a certain grade, which grade may be regarded as zero-grade syzygies—that is to say as many times as any generator is repeated in a group so many such zero-grade syzygies of that type will there be of the corresponding grade.

Let G be a proper generating function to a system of quantics $\Gamma_1, \Gamma_2, \Gamma_3 \ldots$ generating-groups such that

$$G = \frac{1}{\Gamma_0 . \Gamma_1 . \Gamma_2 . \Gamma_3 \ldots}$$

then, as suggested to me by Mr. Franklin, in order that the Γ series may be representative of complete systems of irreducible syzygies of the successive grades it is necessary that $\frac{1}{\Gamma_0} - G$; $\frac{\Gamma_0}{\Gamma_1} - G$; $\frac{\Gamma_0\Gamma_1}{\Gamma_2} - G$; $\frac{\Gamma_0\Gamma_1}{\Gamma_2\Gamma_3} - G$; ... shall, when developed in series of factors with omni-positive indices, be alternately omni-positive and omni-negative. But the existence of these inequalities, although a necessary, is not a sufficient condition in order that the Γ's shall be so representative; ex. gr. $\Gamma_0 . \Gamma_1$ and $\Gamma_2 . \Gamma_3$ might evidently be regarded as single groups and the inequalities would still be satisfied: but suppose we further limit the Γ's in succession by the following rule, viz. that on withdrawing any one of the generator-factors from Γ_0 and calling Γ_0' the group so reduced $\frac{1}{\Gamma_0'} - G$ is no longer omni-positive, this will serve to define Γ_0 absolutely: Γ_0 being so determined, Γ_1 may in like manner be limited by the condition that its quotient by any one of its generators being called Γ_1', $\frac{\Gamma_1'}{\Gamma_0} - G$ shall be no longer omni-negative: then

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Γ_1 is accurately determined, and, proceeding in like manner with each group in succession, the whole system of groups becomes exactly defined, and thus we obtain the necessary and sufficient condition of group-representation.

Calling $\frac{1}{\Gamma_0}, \frac{\Gamma_1}{\Gamma_0}, \frac{\Gamma_1\Gamma_2}{\Gamma_0}, \frac{\Gamma_1\Gamma_3}{\Gamma_0\Gamma_2}, \ldots \nu_0, \nu_1, \nu_2, \nu_3 \ldots$ respectively,

the ν series of quantities stand to G in somewhat the same relation as the complete quotients of a continued fraction to its complete value. Observe that $\nu_0 - 1, \nu_1 - 1, \nu_2 - 1, \ldots$ each vanish when the variables in G are each zero, and become infinite when the variables in G are each unity.

When each such variable has any value intermediate between 0 and 1, I think it almost certain that no two of the ν's can become equal, so that for all values of the variables inside those limits the parabolic lines or surfaces or hypersurfaces, &c., represented (after introducing a new variable ω) by the equations $\omega - \nu_0 = 0, \omega - \nu_1 = 0, \omega - \nu_2 = 0 \ldots$ (which coincide for the limiting values of the original variables at the origin and at a point at infinity) will never intersect, so that within the prescribed limits $\nu_0 - \nu_2, \nu_2 - \nu_4, \nu_4 - \nu_6 \ldots$ will be always positive and $\nu_1 - \nu_3, \nu_3 - \nu_5, \ldots$ will be always negative, the limited boundaries represented by

$$\omega - G, \ \omega - \nu_0, \ \omega - \nu_2, \ \omega - \nu_4, \ldots$$

being each external to the one that precedes it on one side of $\omega - G$, and

$$\omega - G, \ \omega - \nu_1, \ \omega - \nu_3, \ \omega - \nu_5, \ldots$$

following the same law on the other side. It is possible, moreover, that a more stringent condition than the above may be verified, viz., that

$$\nu_0 - G, \nu_2 - \nu_0, \nu_4 - \nu_2 \ldots .$$
$$G - \nu_1, \nu_1 - \nu_3, \nu_3 - \nu_5 \ldots .$$

may each be developable into omni-negative functions, and again (to complete the analogy with the parallel theory of continued fractions or converging continued products) that

$$\nu_0 - G, \ G - \nu_1, \ \nu_2 - G, \ G - \nu_3, \ \nu_4 - G, \ldots .$$

shall form a single series of continually decreasing quantities, or even in their developed state, of functions in which the corresponding coefficients to each facient form a continually decreasing (or, at least, never-increasing) series of

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numbers. Thus in the case of a cubic (quantic in two variables) the curves $u-v_1, u-v_2, \ldots u-v_7, u-v_8, u-v_9$ *form an infinite series of loops having one common asymptote and one common point of intersection at infinity, except as that one point is to each other.*

I annex tables (pp. 59, 60, of the Fundamental Syzygants* of the pleasure which will be felt by the reader in the quintic and sextic rendered more complete by inserting entries corresponding to the fundamental invariants. The positive integers correspond to these latter, the negative integers the negative sign being set over the figure, to the irreducible syzygants. Thus ex. gr. in the table to the sextic the positive integer 2 † and in the 6th line and 4th column indicates that there are 2 groundless variants of degree-order 6, 6. The negative integer 7 found in the 12th line and 12th column indicates that there are 7 irreducible syzygies of deg-order 12, 12 ‡. The negative sign is appropriate, inasmuch as every independent syzygy of any deg-order j vers by a unit the number of linearly independent in- or covariants of that deg-order that can be produced out of the inferior groundforms, so that syzygants may be regarded as negative existences in regard to groundforms: carrying on the same idea, or inter-syzygants might be numbered by integers carrying two negative signs or unaffirming each other, and so on indefinitely.

The method of partitions or generating functions, which leads to these surprising constructions, looks at invariants and their connexions solely with regard to their deg-order or type without taking any account of their content: in other words it deals only with the *idea* or *notion* of these beings and their relations.

* N. B.—A syzygant to a Quantic is a rational integer function of its in- or covariants which, expressed as a function of the coefficients, vanishes identically, but we may still understand its "degree in the coefficients" to mean the degree of any one of the terms of which it is the sum.

† If j or i exceed the highest degree or order respectively found in any table, or, if without that being the case there is a blank space in the j^{th} line and i^{th} column of the table, the meaning is that there is no irreducible groundform or syzygy of the deg-order j, i. In the tables exhibited it will be seen that the deg-order j, i of each syzygant is superior to the deg-order j, i of every groundform: *i. e.* the difference $j-j, i-i$ are neither of them less and one of them is greater than zero. The same is true for all quantics which have a finite Rep. G. F., but not necessarily and probably never actually so in other cases: thus ex. gr. to the seventhic belongs an irreducible invariant of degree 22 and an irreducible syzygy of degree 20, so that here the j, i 20.0 is inferior to the j, i 22.0. The fact of every j, i being superior to the j, i can be expressed by saying that the invariantive syzygetic portions of a Rep. G. F. table are not intermingled but lie totally apart and may be divided from each other by a single continuous cut.

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and may therefore, I think, suitably be termed the Idealistic method.* I cannot see the faintest possibility of the symbolic method serving to determine a complete system of syzygies in any but the trivial cases of quantics of the 3d or 4th order—the only cases where the infinite procession of beings (syzygants, counter-syzygants, anti-counter-syzygants, etc.,) rising out of each other, comes to a stop—there being for those cases no procession after the 1st step, as is also true of invariants (as distinguished from covariants) for quantics of the 6th order. This is how it came to pass in the infancy of the theory that the number of ground-covariants was supposed to become infinite for quantics beyond the fourth and their ground-invariants for quantics beyond the 6th order.

I think it may be interesting to some of the readers of the Journal to be put in possession of the complete system of irreducible syzygies to a system of two or more quantics, and I select as an easy example the case of a combined quadratic and cubic, reserving the other combinations of which the groundform tables have been published for a subsequent number of the Journal. The super-numerary groundforms for the quadri-cubic system (see this Journal, vol. II, pp. 295, 296,) are of the deg-deg-orders 3.4.0, 1.1.1, 2.1.1, 1.3.1, 2.3.1, 1.2.2, 1.1.3, 0.3.3, where the first and second numbers express the degrees in the coefficients of the quadric and cubic respectively, and the last number

* My proof in the *Phil. Trans.*, founded on the canonical form of the Quintic, of its 4th, 8th, 12th and 18th-degreed invariants forming a complete system, the late Mr. Boole's discovery of the cubinvariant to the Quartic, the various disproofs in the *Comptes Rendus* and in this Journal of the existence of supposed groundforms, are all exemplifications of the Realistic point of view. The symbolic lies between this and the Idealistic aspect of the subject, in so far as the operations by which invariants are engendered constitute a new and so to say finer subject-matter, capable of being itself operated upon in all respects like ordinary algebraical substance. In Professor Cayley's 10th Memoir on Quantics there is a sort of half return from the Idealistic to the Realistic view—a kind of substantiality being attributed to the groundforms themselves as primary elements in the study of their syzygetic interconnections. It may be well to notice, for the benefit of the readers of that memoir (*Phil. Trans.* 1878,) that in the Representative Form given at p. 657 two terms are omitted by an oversight, viz. — $a^{11}x^4$ and a^3x^{12}. I need hardly add (since the publication of my tables in this Journal), with reference to a doubt expressed by Prof. Cayley (*loc. cit.*), that I *had* obtained the form referred to in the paragraph following the R. G. F. in question, though *not* by dividing out the common factors from the numerator and denominator of the R. G. F.; on the contrary, the N. G. F. is first obtained from the generating function in its crude form (which if left in that form would lead to a divergent series), and then the R. G. F. is obtained from this, through multiplying its numerator and denominator by the factors needed to render the denominator a product of representative groundforms.

The Symbolic and the Idealistic (which I formerly called the fatalistic or peprotic) method alike, as far as is known, owe their conception to the same (unnecessary to be named) acute and capacious intellect. Whether very much that is essential, remains to be added to the great discoveries of Gordan and Jordan in the direction of the former may reasonably be doubted, but no such misgiving can be entertained with respect to the latter, which already has given rise to many more questions than it has settled (of a kind, too, of which a solution sooner or later may reasonably be anticipated).

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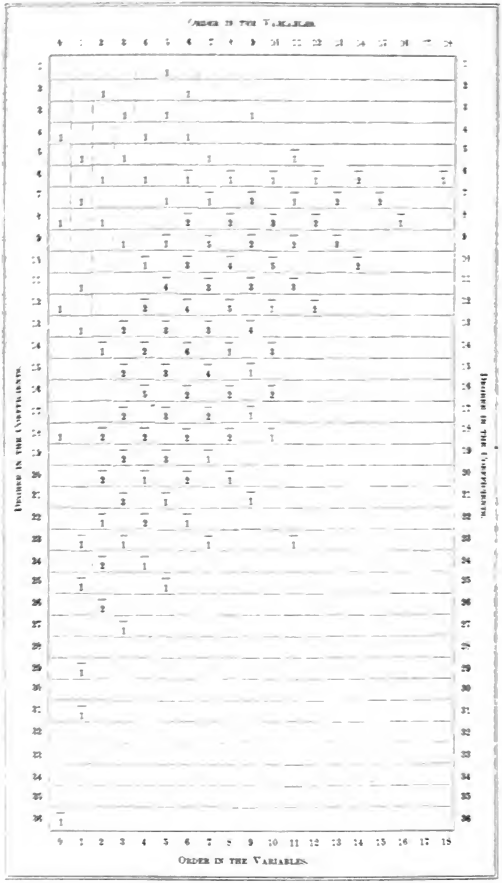

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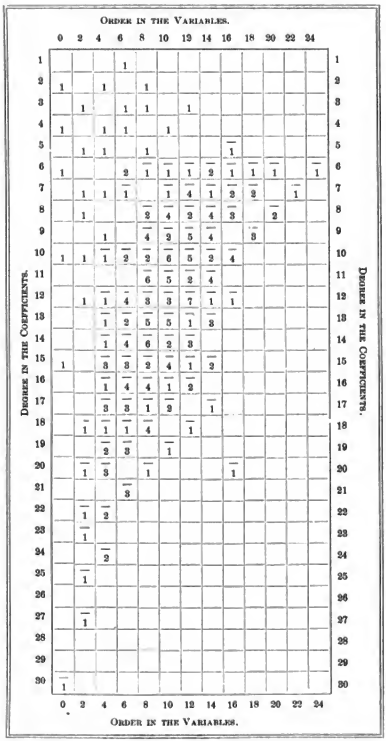
Table of Groundforms and Irreducible Syzygies to the Sextic.


ORDER IN THE VARIABLES.
0 2 4 6 8 10 12 14 16 18 20 22 24
DEGREES IN THE COEFFICIENTS.
DEGREES IN THE COEFFICIENTS.
ORDER IN THE VARIABLES.

expresses the order in the variables. Adding each of these types to itself and every other, rejecting the combinations 2.2.2. 3.3.3. 5.4.3. which appear in the numerator of the *G. F.* and arise from the addition 1.1.1 − 1.1.1. 1.1.1 + 2.1.1. 1.1.1 − 1.3.1., replacing them by the lower combinations 1.1.1 + 1.1.1 − 1.1.1. 1.1.1 − 1.1.1 − 2.1.1. 1.1.1 − 1.1.1 − 1.3.1. *i.e.* 3.3.3. 4.3.3. 3.5.3. and adding in the 12 types furnished by the negative terms in the numerator of the *G. F.*, the totality of the irreducible syzygies (4 in number), to the binary quadricubic system is arrived at and exhibited in the annexed table, in which the exponents attached to any type signify the number of irreducible syzygies of the corresponding degree-order.

Table of Irreducible Syzygies to the Quadricubic System.

6.6.0, 4.5.1, 4.7.1. 5.5.1. 5.7.1. 2.6.2. 3.4.2^A. (3.6.2β, 4.2.2, (4.4.2β. (4.6.2^A. 1.5.3. 2.3.3. (2.6.3^A. (3.3.3β, (3.5.3β. 3.6.3. 3.7.3. 4.3.3. 4.5.3. 1.4.4. 1.6.4. 2.2.4, (2.4.4)^A. 2.6.4. 3.2.4. 3.4.4. 3.6.4. (1.5.5β, 2.3.5, 2.5.5, 3.5.5. 0.6.6. 1.3.6. 1.4.6. 2.2.6, 4.7.6,

there being thus one irreducible invariantive syzygy and 4. 10. 12. 11. 5. 5 covariantive syzygies of orders 1, 2. 3. 4. 5. 6 respectively.

It may be worth while just to notice that the types to the complete system of irreducible syzygies to a simultaneous linear and quartic form will consist simply of the sums of the 13 supernumerary types. (A. M. J., vol. II. p. 235.) 6.3.0, 3.1.1, 3.2.1, 5.3.1, 2.1.2, 2.2.2. 4.3.2. 1.1.3. 1.2.3. 3.3.3, 2.3.4, 1.3.5, 0.3.6. added each to itself and every other, together with the 14 types taken from the negative terms in the numerator of the *G. F.*, viz: 7.3.1, 6.3.2, 5.3.3, 4.3.4. 6.4.4, 6.5.4, 3.3.5, 5.4.5, 5.5.5, 2.3.6. 4.4.6, 4.5.6. 1.3.7, 7.6.7, making $\frac{13.14}{2} + 14$, *i.e.* 105 in all. In this instance there is no rejection or substitution of sums called for.

A word or two seems necessary to leave unambiguous the meaning of the term syzygants of any specified grade in what precedes.

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In- or- covariants may be termed syzygants of grade zero (as already stated). Syzygants of the first grade are defined to be rational integer functions of those of grade zero which vanish when the latter are expressed in terms of the original coefficients. It is not *necessary* to define *these* syzygants as functions of *irreducible* ones of grade zero (which vanish under the condition aforesaid), because every in- or- covariant is a rational integer function of the irreducible in- or- covariants. But when we come to syzygants of the second grade (since those of the first grade are not necessarily functions of the irreducible ones of that grade, but may be so of the in- or- covariants as well), it becomes necessary to define syzygants of the second grade (*aliter* counter-syzygants) as rational integer functions of *irreducible* ones of the first grade which vanish when they are expressed in terms of the quantities (here the in- or- covariants) which immediately precede them in the scale of generation. And so, in general, following out the defining process step by step, by a syzygant of the $(i+1)^{\text{th}}$ grade for the purpose of this theory, is to be understood a rational integer function of the *irreducible* ones of the i^{th} grade which vanishes when these latter are expressed in terms of those of the grade $i-1$. Such at least is my present impression; but, supposing that I am laboring under a misconception on this point, it will in nowise affect the validity of the theory in what regards the computation of the irreducible in- or- covariants and the syzygants of the first grade.

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A Demonstration of the Impossibility of the Binary Octavic possessing any Groundform of deg-order 10 . 4.

By J. J. Sylvester.

Dr. von Gall has rendered an inestimable service to algebraical science by working out, according to Gordan's method, the complete system of groundforms to the octavian binary quantic $[x\ .\ y]^8$. His results, published in the *Mathematische Annalen*, were at first widely discordant from those which have appeared in this Journal, but eventually have been brought by their author into perfect agreement with them, with the sole exception that his table includes a covariant *of deg-order* 10 . 4, not included in my list, which he states that he has not been able to decompose: it is the object of the present communication to bring the two tables into exact accord by demonstrating that no irreducible covariant to $(x\ .\ y)^8$ of that deg-order can exist. The total number of covariants of deg-order 10 . 4 obtained by multiplying together the irreducible covariants of an inferior deg-order (which appear equally in von Gall's table and in my own, and whose existence therefore may be taken for granted)* will be seen to be 32, which is the number of linearly independent covariants of that deg-order given by Cayley's law, (see p. 80); hence, by the fundamental postulate, the 32 compounds in question must not be supposed subject to any linear relation, so that, according to that postulate, there exists no groundform of the deg-order in question; but my object is to use this instance as another exemplification of the validity of that

* As I have elsewhere remarked, since no groundforms can exist exterior to the tables furnished by *Gordan's method*, and no reducible forms can be contained in the tables furnished by the English *method*, it *follows*, even without assuming the truth of the fundamental postulate, that wherever the tables furnished by the two methods accord, they must, of logical necessity, be correct, *mere errors of calculation excepted*.

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same very reasonable postulate—as I have done on the three former occasions where the tables of Clebsch, Gordan and Gundelfinger comprised groundforms extraneous to the tables obtained by me on the assumption of its truth; the proof, however, on the present occasion, is much lengthier than any that has ever hitherto been employed, and involves arithmetical computations of considerable prolixity, all necessity for which I had, in previous cases, been able to evade. It is, I may add, only after repeated trials and discomfitures, that I have succeeded at length in devising a special method adequate to prove the important point at issue.

The irreducible invariants and covariants of deg-order *inferior* to 10.4, (*i. e.* whose degree in the coefficients and whose order in the variables are not each as great as 10 and 4 respectively,) and which also can enter as factors of a covariant of deg-order 10.4 (this excludes the necessity of considering invariants of degrees 9 or 10) are as follows: the invariants are of degrees 2, 3, 4, 5, 6, 7, 8, one of each degree; the covariants are one of deg-orders 5.2, 2.4, 3.4 respectively, and two of deg-orders 4.4, 5.4, 6.4, 7.4, 8.4 respectively. We may denote the invariants by 2.0, 3.0, 4.0, 5.0, 6.0, 7.0, 8.0, and the covariants by 5.2, 2.4, 3.4, 4.4, 4.4*, 5.4, 5.4*, 6.4, 6.4*, 7.4, 7.4*, 8.4, 8.4*, and it is an easy arithmetical calculation to show (see *Comptes Rendus*, July 25, 1881) that there are (as already stated) 32 different ways in which these duads, by their combination, can give rise to the duad 10.4. Out of these 32 it is important, with a view to what follows, to isolate those in which neither 2.0 nor 3.0 appears; their number will easily be seen to be 10, as shown in the scheme below—

$4.0+6.4$	$4.0+6.4^*$	$4.0+4.0+2.4$	$5.0+5.4$	$5.0+5.4^*$
$6.0+4.4$	$6.0+4.4^*$	$7.0+3.4$	$8.0+2.4$	$5.2+5.2.$

What I have to prove is, that no equation $\Omega = 0$ exists, where Ω is a linear function of the 32 products in question, connected by numerical coefficients. Suppose it can be shown that Ω does not contain any of the 10 functions above indicated. Then Ω is either of the form $(2.0)U$ or $(3.0)V$, or is a linear function of $(2.0)U$ and $(3.0)V$. In the former two cases we should obtain $U=0$ or $V=0$ respectively; and in the third case the equation $\lambda(2.0)U+\mu(3.0)V=0$, since 2.0 and 3.0 have no common factor, implies the existence of an integral equation $\lambda\frac{U}{(3.0)}+\mu\frac{V}{(2.0)}=0$. Hence, in the

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I take for the primitive the special form $(0,\ b,\ 2c,\ d,\ 0,\ 0,\ 0,\ 0,\ 1)[x,\ y)^8$, that is to say, $8bx^7y + 56cx^6y^2 + 56dx^5y^3 + y^8$, with the relation $bd = 3c^2$, and proceed to form the required derivatives in conformity with von Gall's scheme of derivation. I use, as the best practical method of obtaining the "alliance" of the i^{th} order between any two forms ϕ, ψ (of the orders μ, ν) denoted by $(\phi,\ \psi)_i$, the lineo-linear quadrinvariant (with respect to the variables of emanation) of the i^{th} emanant of ϕ combined into a system with the i^{th} emanant of ψ, taking care to reduce the result to the *parenthetical* form $(\ldots\ldots)[x,\ y)^{\mu+\nu-2i}$, containing only integer coefficients free from any common numerical factor. For the sake of brevity, too, I omit in general the symbolical factor containing $(x,\ y)$: so that $(a_0,\ a_1,\ a_2,\ \ldots,\ a_i)$ will indicate the same thing as $(a_0,\ a_1,\ a_2,\ \ldots,\ a_i)[x,\ y)^i$. I shall adhere, in what follows, to the notation employed by Dr. von Gall.

We have then, according to this notation,

$$f = (0,\ b,\ 2c,\ d,\ 0,\ 0,\ 0,\ 0,\ 1) \quad . \quad . \quad . \quad (1)$$

$$\begin{aligned} i = (f,\ f)_4 &= (4bx^3y + 12cx^2y^2 + 4dxy^3)y^4 - 4dx^4(bx^4 + 8cx^3y + 6dx^2y^2) \\ &\qquad + 3(2cx^4 + 4dx^3y)^2 \\ &= [12c^3 - 4bd,\ 16cd,\ 24d^2,\ 0,\ 0,\ 4b,\ 12c,\ 4d,\ 0][x,\ y]^8, \end{aligned}$$

where the square bracket is employed to signify the same thing as would be indicated by the use of the round clamp, with the exception that the binomial coefficients are suppressed. We have, therefore, introducing the multipliers

$$\frac{14}{1},\ \frac{14}{8},\ \frac{14}{28},\ \frac{14}{56},\ \frac{14}{70},\ \frac{14}{56},\ \frac{14}{28},\ \frac{14}{8},\ \frac{14}{1},$$

$$i = (0,\ 28cd,\ 12d^2,\ 0,\ 0,\ b,\ 6c,\ 7d,\ 0) \quad . \quad . \quad . \quad . \quad . \quad . \quad (2)$$

$$\begin{aligned} k = (f,\ f)_6 &= (2bxy + 2cy^2)y^3 - 10d^2x^4 \\ &\equiv (\overline{2}0d^2,\ 0,\ 0,\ b,\ 4c)^* \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad (3) \end{aligned}$$

$$\begin{aligned} \Delta = (k,\ k)_8 &= \overline{2}0d^2x^3(2bxy + 4cy^2) - b^2y^4 \\ &\equiv (0,\ 90c^2d,\ 40cd^2,\ 0,\ 3b^2) \quad . \quad . \quad . \quad . \quad . \quad . \quad (4) \end{aligned}$$

$$C = (k,\ k)_4 = \overline{2}0d^2 \,.\, 4c \equiv cd^2 \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad (5)$$

$$\begin{aligned} f_4 = (f,\ k)_4 &= 4c(4bx^3y + 12cx^2y^2 + 4dxy^3) - 4b(bx^4 + 8cx^3y + 6d)x^2y^2 + \overline{2}0d^2y^4 \\ &= -4b^2x^4 - 16bcx^3y + (48c^2 - 24bd)x^2y^2 + 16cdxy^3 - 20d^2y^4 \\ &\equiv (b^2,\ bc,\ c^2,\ c\overline{d},\ 5d^2) \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad (6) \end{aligned}$$

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* The sign of equivalence ($\equiv$) is used in the above and in what follows in the sense of "may be superseded by."

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$$f_{7,3} = f_{7,4} + \dots$$

$$\equiv \dots$$

$$f_{7,2} = f_{7,3} + \dots$$

$$= \dots$$

$$f_{7,1} = f_{7,2} + \dots$$

$$= \dots$$

$$f_{7,0} = f_{7,1} + \dots$$

$$\equiv \dots$$

$$f_{7,-1} = f_{7,0} \Delta_1 = \dots$$

$$= \dots$$

$$\equiv \dots$$

$$f_{7,-2} = f_{7,-1} \Delta_1 = \dots$$

$$= \dots$$

$$\equiv \dots \quad (10)$$

$$f_{7,-3} = f_{7,-2} \Delta_1 = \dots$$

$$= \dots$$

$$\equiv \dots \quad (11)$$

$$f_{7,-4} = f_{7,-3} \Delta_1 = \dots$$

$$= \dots$$

$$\equiv \dots \quad (12)$$

$$f_{6,-4} = f_{7,-4} \Delta_1 = -4(3\mathfrak{y}^6 + 6\mathfrak{y}^5) + 6(4\mathfrak{y}^5 + 3\mathfrak{y}^4) \cdot \mathfrak{y}^4$$

$$= 3\mathfrak{y}^4 + 12\mathfrak{y}^5 + 24\mathfrak{y}^6$$

$$\equiv \mathfrak{y}^4 + 20\mathfrak{y}^6 \quad (13)$$

$$f_{5,-4} = f_{6,-4} \Delta_1 = -4(3\mathfrak{y}^6 + 6\mathfrak{y}^5) + 6(4\mathfrak{y}^5 + 3\mathfrak{y}^4)(7\mathfrak{y}^6 + 3\mathfrak{y}^5)$$

$$= 1008\mathfrak{y}^5 + 3312\mathfrak{y}^6 \equiv 7\mathfrak{y}^5 - 23\mathfrak{y}^6.$$

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The term involving c^3d^4 being a multiple of the square of C (the invariant of the 4th degree) may be neglected, and, instead of $i_{8,3}$, we may write the irreducible invariant of the 8th degree (say) $I_8 = b^3c^3$. . . . . (14)

That of the 7th degree we have just found $= b^4 + 200c^3d^2$; and obviously the quadrinvariant of f is identically zero, or say $I_2 = 0$. . . . (15)

Also the cubinvariant $I_3 = (f, i)_8$, where

$$f = (0,\ b,\ 2c,\ d,\ 0,\ 0,\ 0,\ 0,\ 1)$$

and $$i = (0,\ 28cd,\ 12d^2,\ 0,\ 0,\ b,\ 6c,\ 7d,\ 0).$$

Hence $$I_3 = -56bd + 336c^3 - 168bd = 504c^3 - 168bd = 0, \quad . \quad (16)$$

and we have found $I_4 \equiv cd^2$.

Also, $I_5 = (f, k^2)_8$ where

$$k^2 = (10d^2x^4 - 2bxy^3 - 2cy^4)^2$$
$$= 100d^4x^8 - 40bd^2x^5y^3 - 40cd^2x^4y^4 + 4b^2x^3y^6 + 8bcxy^7 + 4c^2y^8$$

Hence $$I_5 = 100d^4 + 2c \cdot 4b^2 - b \cdot 8bc \equiv d^4.*$$

The only remaining irreducible required for present purposes is I_6, represented by $(i_4, k)_4$ where

$$k = [\overline{10}d^2,\ 0,\ 0,\ 2b,\ 2c][x, y]^4,$$

and

$$i_4 = (336c^3,\ 92c^2d,\ 72cd^2,\ 140d^3,\ 4b^2)(x, y)^4.$$

Hence

$$I_6 = \overline{40}b^2d^3 - (2b)\,92c^2d + 2c(336c^3)$$
$$= (-360 - 552 + 672)c^4 \equiv c^4.$$

On proceeding to form the 10 compound covariants of deg-order 10.4 obtained by suitable combinations of the invariants and covariants of inferior deg-order, it will be found that the following 13 arguments will make their appearance, in which, for greater brevity, x and y are each taken equal to unity, which in nowise affects (favorably or unfavorably) the course of the reasoning: these arguments are

$$b^4,\ c^2,\ c^2d^2;\quad b^2c,\ c^2d,\ cd^2;\quad b^4c^2,\ c^3d^2,\ d^3;\quad b^2c^2,\ c^4d^2;\quad b^2c^4,\ c^3d^4,$$

where the 5 groups of arguments, separated from one another by semicolons,

---

* It will of course be recognized that the lineo-linear quadrinvariant to the system

$$(a_0, a_1, a_2, \ldots a_8)(x, y)^8,\ [b_0, b_1, b_2 \ldots b_8][x, y]^8$$

is simply $$a_0b_8 - a_1b_{8-1} + a_2 \cdot b_{8-2} \ldots \pm a_8b_0:$$

the disappearance of the argument b^3c from companionship with d^4 in I_5 is rather remarkable, and could not have been predicted. This circumstance considerably simplifies the subsequent calculations.

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are elements of the coefficients of x^4, x^3y, x^2y^2, xy^3, y^4, and when supplemented by such powers of k (of weight 8) as will bring their degrees up to the number 10, are of the respective weights 38, 39, 40, 41, 42, which is right, since the weight of the differentiant of deg-order 10.4 to $(x, y)^4$ is $\frac{10.8-4}{2}$, *i.e.* 38; for greater brevity (in what precedes) k, the coefficient of y^8 in f, has been made unity, and it is worthy of notice that all the arguments that can appear consistently with the law of weight are represented by these 13, upon the understanding that any power of bl in an argument is replaceable by the like power of c^2.

But it is further noticeable that the 10 compounds in question, although apparently linear functions of 13 arguments, are virtually such of only 11: for it will be seen that $h^4 + 4h^2c + 6h^2c^2$ may be regarded as a single argument, none of the three simpler arguments which appear in it occurring except in two of the 10 compounds, and their coefficients in each of those two being in the ratio 1 : 4 : 6.

Had the contraction in the number of really independent arguments extended two steps further, so that the 10 compounds had been linear functions of only 9 quantities (as might, for anything that could be known *à priori*, have been the case), they would necessarily have been linearly connected, and no inference could have been drawn from the particular value assigned to f: moreover, had the 10 compounds been linear functions of only 10 quantities, although the particular form might have been sufficient for drawing a positive inference as to the non-existence of the general syzygy $\Omega = 0$, still there would have been no room for applying the all-important *test* of the correctness of the arithmetical computations upon which that inference would have reposed; and it would have been very unsatisfactory and unphilosophical to have made so important a conclusion rest upon the negative fact of a determinant of the 10th order *not vanishing*, when the undisproved existence of a single error committed in the many hundreds (or even—it might be said—thousands) of arithmetical steps involved in the calculations of the elements of that determinant would have been sufficient to account for its value differing from zero.

Fortunately, as will be seen, the correctness of the calculations may be *verified* (thanks to the existence of elements one more than barely sufficient—viz., 11 instead of 10) by the *positive* fact of a certain determinant of the 11th order being found equal to zero. It has often seemed to me that a special

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providence or pre-established harmony in the intellectual world brings it about that honest labor, persevering in the pursuit of an important truth in the face of doubts and difficulties and repeated disappointments, shall not in the end lose its due reward.*

Let us now denote the quantities $b^8 + 4b^5c + 6b^4c^2$, c^3, c^2d^2; $4c^3d$, $4cd^2$; $6c^2d^2$, $6d^2$; $4b^3c^3$, $4c^4d^2$; b^2c^4, c^6d^4 by A, β, γ, δ, ε, ζ, η, θ, $\varkappa$, λ, μ, respectively, and denote the covariants of the order 4 that have been calculated in what precedes according to their deg-order—viz., let us call

$(f_{4,3})^2$; $i_{8,3}$; i_8; $f_{4,3}$; f_4; Δ; i_4; f_4; k

10 . 4; 6 . 4; 6 . 4*; 5 . 4; 5 . 4*; 4 . 4; 4 . 4*; 3 . 4; 2 . 4 respectively, then the values of 10 . 4, $I_4 \times 6 . 4$, $I_4 \times 6 . 4^*$, $I_5 \times 5 . 4$, $I_5 \times 5 . 4^*$, $I_6 \times 4 . 4$, $I_4 \times 4 . 4^*$, $I_3 \times 3 . 4$, $I_3^2 \times 2 . 4$, $I_6 \times 2 . 4$, will be as shown in the table annexed

A	β	γ	δ	ϵ	ζ	η	θ	$\varkappa$	λ	μ	
3	$\overline{3240}$	1200	3510	$\overline{3000}$	1740	$\overline{5000}$	3	450	3	.	. . (1)
.	.	$\overline{360}$	126	$\overline{350}$	49	.	.	19	.	$\overline{138}$	. . (2)
.	.	240	63	.	$\overline{63}$	.	.	$\overline{120}$	.	$\overline{90}$	. . (3)
.	.	$\overline{120}$	81	60	54	$\overline{100}$	.	27	.	60	. . (4)
.	.	40	27	80	18	.	.	9	.	.	. . (5)
.	.	.	90	.	40	.	.	.	3	.	. . (6)
.	336	.	92	.	72	.	.	140	4	.	. . (7)
1	1800	.	600	.	200	.	3	$\overline{200}$	45	1000	. . (8)
.	.	$\overline{20}$	.	.	.	.	.	3	.	4	. . (9)
.	$\overline{180}$	.	.	.	.	.	1	.	4	.	. .(10)

Line (1) of course signifies $3A - 3240\beta + \ldots + 3\lambda$.

(2) . . . . . $-360\gamma + 126\delta \ldots - 138\mu$,

and so for all the other lines, each being a linear function of the 11 quantities $A, \beta, \ldots, \lambda, \mu$.

* I began with taking as a special form $ax^8 + by^8 + cz^8$, with the relation $x + y + z = 0$ (which, like the form f, contains two arbitrary ratios,) and went through the very considerable labor of calculating all its inferior derivatives capable of entering into the composition of a covariant of deg-order 10 . 4, but the result turned out altogether nugatory.

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Consequently, it only remains to ascertain whether the complete minors all disappear in the matrix of the dimensions (6 × 5) given below, viz:

$$\begin{matrix} 5 & 2 & . & . & 5 & . \\ 2 & . & . & . & 3 & 4 \\ 7 & 5 & 3 & 7 & 9 & . \\ 9 & 8 & . & 3 & 1 & 9 \\ 3 & 5 & 2 & 5 & 8 & 5 \end{matrix}$$

If all the complete minors of this matrix contain 11, the same must be true of the determinant formed by subtracting the first column in the above from the fifth and substituting the difference in place of the fifth column, *i. e.*

$$\begin{vmatrix} 2 & . & . & . & . \\ . & . & . & 1 & 4 \\ 5 & 3 & 7 & 2 & . \\ 8 & . & 3 & 3 & 9 \\ 5 & 2 & 5 & 5 & 5 \end{vmatrix} \text{ and therefore } \begin{vmatrix} . & . & 1 & 4 \\ 3 & 7 & 2 & . \\ . & 3 & 3 & 9 \\ 2 & 5 & 5 & 5 \end{vmatrix}$$

should contain 11, and (as we may see by substituting the excess of 4 times the 3d column over the fourth in place of the 3d) the same must be true of the determinant $\begin{vmatrix} 3 & 7 & 8 \\ . & 3 & 3 \\ 2 & 5 & 4 \end{vmatrix}$ of which the value is $3(12-15)+2(21-24)$, *i. e.* -15, and as this does not contain 11, it follows that the complete minors of the matrix which expresses the 10 compounds as linear functions of the 11 arguments α, β, $\gamma \ldots \lambda$, μ are not all zero, and they are consequently not linearly connected.* But, obviously, the calculations on which this proof

* In the *Comptes Rendus* for 23d August of this year, I have given a brief *résumé* of the contents of this paper. At page 367 of that fascicule, (third line from foot,) in the last line but one of the matrix, I have written 9 8 . 8 1 9 in error for 9 8 . 3 1 9 (having mistaken a 3, *covered with a blot*, for 8); consequently, the calculations which follow page 368 of the *C. R.* are erroneous. Fortunately, I did not repeat the mistake in calculating the value of the determinant subsequently given of the 11th order in proving that it contains the divisor 11. Moreover, this determinant, or rather its remainder to modulus 11, has been calculated by an entirely different process by Mr. Morgan Jenkins (whose work is before my eyes), and with the same result of its being divisible by 11. This instance shows how unsafe it would have been to have trusted to the fact of the minors not vanishing, unsupported by the positive evidence which the determinant of the 11th order affords of the preceding calculations, as regards the values of the groundforms, being unaffected with *one single error* in spite of the vast number of processes of addition, subtraction, multiplication, division, transposition, transcription and change of sign employed in working them out.

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depends imperatively on a verification as to which it would be more easy than to bring out some or all of the minute different from zero by a single error of calculation or slip of the pen. To this end I examine the value of von Gra...'s undecomposed covariant for the assumed special form f and shall show that the 10 compounds and the 11th function θ become linearly connected, i. e. subject to a syzygy, on the assumption that the arithmetical values of the coefficients have been correctly calculated.

The function in question, Dr. von Gra...'s i_4, is obtained as follows:

$F = (i, \Delta_3)$ of deg-order 6, 8 is equal to

$(16\alpha^2\beta^2y + 12\alpha\beta^3x^2 + 6\alpha^2\gamma^2 + 8\alpha\beta\gamma^2, 4\alpha^2\beta^2 - 2\beta^4$

$-(16\alpha^2\beta\delta + 16\alpha\beta^2\gamma)(2\alpha\beta^2x^2 + 72\beta^2xy + 12\alpha^2y^2 + 3\alpha\gamma y^2 - 7\beta^2$

$+(12\beta^2\delta + 20\beta\gamma^2 + 9\alpha^2y^2 + 42\beta xy^2 + 18\alpha^2\beta xy - 4\alpha\gamma^2y^2,$

$= [504\alpha^2\beta^2\delta, 856\alpha^2\beta^2\gamma, 384\alpha\beta^3\delta, 504\beta^2\gamma\delta, 756\alpha^3\beta^2\delta, 432\alpha^2\beta^3\gamma,$

$180\beta^4 + 504\alpha^2\beta^2\delta, 192\beta^3\gamma][x, y]^4$

which, multiplied by 28, will be seen to be equivalent to

$(14112\alpha^2\beta^2\delta, 23968\alpha^2\beta^2\gamma, 3840\alpha\beta^3\delta, 7056\beta^2\gamma\delta, 30240\alpha^3\beta^2\delta, 12096\alpha^2\beta^3\gamma,$

$6384\beta^4 + 14000\alpha^2\beta^2\delta, 5376\beta^3\gamma).$

Finally,

$i_4 = (F, \Delta)_4 = 3\beta^2(\overline{14112\alpha^2\beta^2\delta^2} + \overline{11984\alpha^2\beta^2\gamma^2y} + \overline{23968\alpha^2\beta^2\gamma^2}$

$+ 3024\alpha^2\beta\gamma y^3 + 3024\beta^4y^4)$

$+ 6.40\alpha\beta^2(3840\alpha^2\beta^2\delta + 3024\alpha^2\beta\gamma^2y + 18144\alpha^2\beta^2\gamma^2 + 1128\alpha^2\beta\gamma y^2 + 432\alpha^2\beta^2y^3)$

$- 4.90\beta^2(756\beta^2\delta^2 + 1209\alpha^2\beta\gamma y + 16920\alpha^2\beta^2\gamma^2 + 1752\alpha^2\beta^2\gamma y^2 + 63\beta^4 + 1400\alpha^2\beta^2y^4$

which, dividing out by 144,

$\equiv (32130\alpha^2 + 6400\alpha^2\beta^2)\delta^2 + 37590\alpha^2\beta\gamma y + 16380\alpha^2\beta^2\gamma^2 + (63\beta^4 + 2500\alpha^2\beta^2)\gamma y^2$

$+ \left(\frac{819}{2}\beta^2\delta + 2400\alpha^2\beta^2\right)y^4$

$\equiv (128520\alpha^2 + 25600\alpha^2\beta^2, \overline{37590\alpha^2\beta}, \overline{10920\alpha^2\beta^2}, 63\beta^4 + \overline{2500\alpha^2\beta^2},$

$\overline{1638\beta^2\delta} + 9600\alpha^2\beta^2).$

Here it will be noticed that the arguments collected in what I have designated by A, viz. b^4, b^2c, b^2d, do not appear at all in i_4. Had they made their appearance with other than coefficients bearing to each other the ratios of 1:4:6, i_4 could not have been a linear function of the 10 compounds which are linear functions of A and of 10 other arguments. This is in itself, to some extent, a verification of a portion at least of the preceding calculations: i_4, as it turns

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out, is a linear function of only 8 out of the 11 arguments which appear in the other 10 compound covariants, viz. of $\beta, \gamma, \delta, \zeta, \theta, \varkappa, \lambda, \mu$, neither A, ϵ nor η appearing in i_4''.

If the figuring throughout is correct, the determinant represented by the matrix constituted of the coefficients of the 11 compounds, ought to vanish identically; but it will be sufficient for all reasonable purposes (*i. e.* to satisfy any reasonable doubts on the subject) if I show that this is the case for the value of that determinant in respect to three consecutive prime numbers 11, 13, 17 taken almost at hazard.

It must be understood that the vanishing of the determinant in question adds *no additional strength whatever* to the proof—which, by Cayley's law, is perfect without it—provided that the figures in the coefficients of the 10 compounds (excluding i_4'') have been correctly calculated. It is to authenticate these figures, and not to verify the legitimacy of the argument, that the 11th compound is calculated, and the determinant formed by all the eleven shown to contain any number taken at will. It must be remembered that the calculations have been most carefully conducted and verified at each step: consequently, if any person, after the evidence that will be given, entertains any doubt of the correctness of the result, the duty is incumbent on him to put his finger upon some one of the coefficients of the 10 first compounds and prove it to be incorrectly stated.

First, for the modulus 11. In respect to this modulus, the coefficients in i_4'' of

$$A, \eta, \theta, \beta, \lambda, \gamma, \delta, \epsilon, \zeta, \varkappa, \mu$$

are congruous to

$$0, 0, 8, 4, 1, 8, 8, 0, 3, 3, 8.$$

Hence, (making use of the transformations already calculated of the upper half of the rectangular matrix), it has to be shown that 11 is a divisor of the determinant of the 9th order

8	4	1	8	8	.	3	3	8
10	5	.	4	4	.	10	9	.
	10	7	7	7	.	1	2	.
		9	2	9	.	10	2	.
			5	2	.	.	5	.
			2	.	.	.	3	4
			7	5	3	7	9	.
			9	8	.	3	1	9
			3	5	2	5	8	5

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The first and second lines of this matrix combined give rise to the line 1 7 7 . 6 9 8, and this, combined with the 4th, to the line 5 1 . . 9 5 under which last, writing the 5 remaining lines

5 2 . . 5 .
2 . . . 3 4
7 5 3 7 9 .
9 8 . 3 1 9
3 5 2 5 8 5

it has to be shown that the determinant to the above matrix of the 6th order contains 11.

Let the fourth line be replaced by 3 times itself + the last line, which, to the modulus 11, reduces the third column to the form of five zeros followed by 2. This shows that we may use, instead of the above, the determinant

5 1 . 9 5
5 2 . 5 .
2 . . 3 4
2 9 4 2 5
9 8 3 1 9;

and again, replacing the fourth line of the new matrix by its double + the last line, we fall upon the matrix

5 1 9 5
5 2 5 .
2 . 3 4
2 4 5 8,

for which we may substitute

5 1 4 5
5 2 . .
2 . 1 4
2 4 3 8,

or (as may be seen by replacing the second column by 3 times itself + the first column) $\begin{vmatrix} 8 & 4 & 5 \\ 2 & 1 & 4 \\ 3 & 3 & 8 \end{vmatrix}$, in which (to modulus 11) the first line is 4 times the second. Hence, the test is satisfied as regards the modulus 11.

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I will next take the modulus 13.

The residues to modulus 13 of the coefficients in i_4''' of

$$\theta \quad \beta \quad \lambda \quad \gamma \quad \delta \quad \varepsilon \quad \zeta \quad \varkappa \quad \mu$$

will be seen to be

$$11 \quad 11 \quad . \quad 10 \quad 6 \quad . \quad . \quad 12 \quad 6$$

and the matrix corresponding to the one of the same dimensions (11×10), previously calculated for modulus 11, will, in respect to modulus 13, become

3	8	3	10	3	4	.	3	11	8	.
1	.	10	6	6	.	2	.	5	8	12
	4	.	.	.	10	3	8	2	1	.
		1	2	4	.	.	.	.	.	.
			11	4	.	1	.	7	10	.
				3	.	12	.	1	1	.
					6	.	.	.	3	4
					1	1	2	5	9	.
					6	11	.	2	10	1
					4	9	1	10	6	5.

In place of the first six of the above lines, applying the same process as before, we may substitute

3	8	3	10	3	4	.	3	11	8	.
	5	1	8	2	9	5	10	4	3	10
		9	7	5	1	8	.	7	6	12
			11	5	12	5	12	6	7	1
				2	11	8	11	11	7	2
					6	.	7	8	7	7.

Combining the i_4''' line (*i. e.* the coefficients of $\theta\ \beta\ \lambda \ldots \mu$ in i_4''' above given) with the third of these, we obtain the line

$$4 \quad 3 \quad 12 \quad 8 \quad . \quad 12 \quad 10 \quad .$$

which, again combined with the fourth of the same, gives rise to the line

$$7 \quad 10 \quad 9 \quad 9 \quad 9 \quad 4$$

Adding on the sixth line, viz. 6 . 7 8 7 7 and the four last lines of the first matrix, viz. the lines marked with an asterisk,

*6	.	.	.	3	4
*1	1	2	5	9	.
*6	11	.	2	10	1
*4	9	1	10	6	5,

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the determinant [illegible] to be a rational function of [illegible] we may [illegible] determinant relative to suffix 11

Substituting for the 1st column twice the 1st plus three times the 4th and for the 4th column twice the 4th plus the 1st and beginning the factor 3 we get [illegible] the determinant

$$\begin{vmatrix} 5 & 11 & 9 & 9 & 11 \\ 4 & . & 7 & 8 & 8 \\ 5 & 1 & 5 & 5 & 4 \\ 9 & 11 & . & 8 & 9 \\ 4 & 9 & 1 & 1 & 4 \end{vmatrix} \quad \text{or} \quad \begin{vmatrix} 5 & 11 & 9 & 9 & 1 \\ 4 & . & 7 & 8 & . \\ 5 & 1 & 5 & 5 & 11 \\ 9 & 11 & . & 8 & 11 \\ 4 & 9 & 1 & 1 & 11 \end{vmatrix}$$

There is one [illegible] for the 4th column the 4th plus twice the 1st say M and for the 5th column I mean the 1st plus the 5th say N we denote in like manner [illegible] determinant

$$\begin{vmatrix} 5 & 4 & 9 & 1 \\ 1 & 8 & 12 & 8 \\ 12 & 9 & 12 & 4 \\ 11 & 4 & 11 & 3 \end{vmatrix}$$

where the 1st column is the M with the zero in it left out and the 4th column the N with the zero in it left out

This by elimination or in any [illegible] the first value is to the left between the successive pairs of lines gives rise to the determinant

$$\begin{vmatrix} 5 & 4 & . \\ 4 & 9 & 4 \\ . & 4 & 3 \end{vmatrix}$$

which is divisible by $11 \equiv 5.1 - 4.8 - 4.4 \equiv 5 - 11 - 16 \equiv 1$.

It remains only to apply the 5th proposed test using 17 as the modulus.

The ζ are here [illegible]

$$11 \quad 9 \quad 11 \quad 5 \quad 14 \quad . \quad 11 \quad 7 \quad 11$$

and the great remainder matrix becomes

$$\begin{matrix} 3 & 5 & 8 & 7 & 8 & 11 & 6 & 5 & 4 & 6 & . \\ 1 & . & 14 & 13 & 11 & . & 5 & . & 11 & 4 & 14 \\ & 2 & . & . & . & 14 & 11 & 5 & 8 & 11 & 7 \\ & & 1 & 7 & 4 & . & . & . & . & . & . \\ & & & 13 & 4 & . & 7 & . & 4 & 4 & . \\ & & & & 8 & . & 5 & . & 4 & . & . \end{matrix}$$

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with 4 more lines, which will be presently supplied in their proper place. For those above written may be substituted

3	2	3	7	3	10	8	9	6	8	.
	15	5	4	13	7	7	8	16	4	8
		7	9	8	5	11	.	13	6	.
			6	3	12	6	.	4	11	.
				2	14	15	.	6	.	.
					9	16	.	11	.	.

Rejecting the first two lines, and writing over the remaining ones the i_4'' line, there results

12	0	11	2	14	.	11	7	12
7	9	8	5	11	.	13	6	.
	6	3	12	6	.	4	11	.
		2	14	15	.	6	.	.
			9	16	.	11	.	.

which may be replaced by

12	0	11	2	14	.	11	7	12
6	2	12	.	.	11	6	1	
6	.	2	.	9	13	11		
16	1	.	1	8	12			
9	16	.	11	.	.			
*14	.	.	.	3	4			

to which I add in the 4 pretermitted lines distinguished by asterisks,

* 6	10	12	1	9	.	
* 2	12	.	5	16	12	
*14	7	7	15	2	15	

and the determinant, represented by the square matrix (6×6) exhibited by the 6 lines last appearing above, ought to contain the modulus 17 as a divisor. Instead of the 3d line from the bottom we may substitute its double less the last line, and thus, neglecting the factor 7, fall upon the matrix

16	1	1	8	12
9	16	11	.	.
14	.	.	3	4
15	13	4	16	2
2	12	5	16	12.

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[illegible] the [illegible] [illegible] [illegible]

ments in the supposed syzygetic function Ω' for the particular form f will be 4.0×3.4 and 5.0×2.4, *i. e.* cd^3 (b^3, bc, c^3, $-cd$, $5d^2$), and d^4 ($20d^2$, 0, 0, b, $4c$), between which obviously no syzygy is possible, so that neither of them can appear in the general form of Ω'. Hence the terms in the general form of Ω' must be divisible all by 2.0 or all by 3.0, or some by 2.0 and some by 3.0, and consequently there must exist a syzygy of the deg-order 5.4, 4.4, or 2.4. The first of these hypotheses has already been shown to be impossible, and the remaining two need not even have been mentioned, as there is only a single compound of the deg-order 4.4, viz. 2.0×2.4, and none of the deg-order 2.4. Lastly, for the deg-order 8.4, still using the same special form of f, the arguments in the supposed syzygetic functions which do not vanish are 4.0×4.4, $4.0\times4.4^*$, 5.0×3.4, and 6.0×2.4, *i. e.*

$$cd^3\,(0,\ 90c^2d,\ 40cd^2,\ 0,\ 3b^2)$$
$$cd^3\,(336c^3,\ 92c^2d,\ 72cd^2,\ 140d^3,\ 4b^2)$$
$$d^4\,(b^2,\ bc,\ c^2,\ -cd,\ 5d^2)$$

and
$$c^4\,(-20d^2,\ 0,\ 0,\ b,\ 4c).$$

The argument d^8 in the 3d of these quantities has no equivalent in any of the other 3. Hence the 3d quantity does not appear in the syzygy: moreover, the 4th compound contains one argument, viz. bc^4, which does not rationally contain d^2c $\left(\text{for } \frac{bc^3}{d^2} = \frac{b^2c}{3d}\right)$. Hence this compound also disappears, and obviously no syzygy connects together the first two. Hence in the supposed general syzygy there exist no compounds containing neither 2.0 nor 3.0, and by the same reasoning as before, this supposed syzygetic function must imply the existence of one of the deg-order 6.4 or 5.4 or 4.4. The two last of the three suppositions have already been seen to be impossible, and the first would imply a linear relation between 2.0×4.4, $2.0\times4.4^*$, 3.0×3.4, 4.0×2.4, the last of which we see, by taking f for the primitive, cannot appear in the general syzygy, and the remaining 3 arguments would imply that the general covariant 3.4 would contain the invariant 2.0, which is absurd. Hence it follows from Dr. von Gall's own results that the existence of a groundform of deg-order 10.4 is impossible. The only principle extraneous to his results made use of is Cayley's all-important rule, of which an irrefragable demonstration has been given by the author of this paper, but which still, as far as he is aware, remains unutilized, and is almost passed over in silence by invariantists of the German school.

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It may be well to make the following observations in order that the nature of proofs of this kind may be perfectly understood. 1. It is evident that the value of the number of linear incongruent solutions of the congruence $x^n - 1 \equiv 0 \pmod{p}$ is n.

Taking then for the proof the polynomial $x^n - 1$, it is easy to see that the following is an identical equation: $x^n - 1 = (x-1)(x-2)(x-3)\ldots(x-n)$. Let the coefficients of the powers of x in the product be denoted by $1, \alpha, \beta, \gamma, \ldots \omega$, so that $\alpha = -(1+2+3+\ldots+n)$, $\beta = 1\cdot2 + 1\cdot3 + \ldots + 2\cdot3 + \ldots$, $\gamma = -(1\cdot2\cdot3 + \ldots)$, $\ldots \omega = \pm 1\cdot2\cdot3\ldots n$.

The value of α is $-\frac{n^2+n}{2}$. It is also evident that the number of linearly independent solutions of $x^n - 1 \equiv 0 \pmod{p}$ given by Lagrange's law, $\frac{1\cdot2\cdot3\ldots p-1}{1\cdot2\cdot3\ldots n\cdot1\cdot2\cdot3\ldots p-1-n}$, is represented by $\frac{v^{n+1}-1}{v-1} - n$, where $v = \frac{n^{n+1}-1}{2} = \frac{n^2+n}{2}$. $v = n-1 \pmod{n}$, i.e. by Euler's Theorem, is the remainder of v^n in the development of

$$\frac{1-v^{n+1}}{1-v} \cdot \frac{1-v^{n+1}}{1-v^2} \cdot \frac{1-v^{n+1}}{1-v^3} \cdot \frac{1-v^{n+1}}{1-v^4} \cdot \frac{1-v^{n+1}}{1-v^5} \cdot \frac{1-v^{n+1}}{1-v^6} \cdot \frac{1-v^{n+1}}{1-v^7} \cdot \frac{1-v^{n+1}}{1-v^8} \cdot \frac{1-v^{n+1}}{1-v^9} \cdot \frac{1-v^{n+1}}{1-v^{10}} \cdot \frac{1-v^{n+1}}{1-v^{11}} \cdot \frac{1-v^{n+1}}{1-v^{12}} \cdot \frac{1-v^{n+1}}{1-v^{13}} \cdot \frac{1-v^{n+1}}{1-v^{14}} \cdot \frac{1-v^{n+1}}{1-v^{15}} \cdot \frac{1-v^{n+1}}{1-v^{16}} \cdot \frac{1-v^{n+1}}{1-v^{17}} \cdot \frac{1-v^{n+1}}{1-v^{18}} \cdot \frac{1-v^{n+1}}{1-v^{19}} \cdot \frac{1-v^{n+1}}{1-v^{20}} \cdot \frac{1-v^{n+1}}{1-v^{21}} \cdot \frac{1-v^{n+1}}{1-v^{22}} \cdot \frac{1-v^{n+1}}{1-v^{23}} \cdot \frac{1-v^{n+1}}{1-v^{24}} \cdot \frac{1-v^{n+1}}{1-v^{25}} \cdot \frac{1-v^{n+1}}{1-v^{26}} \cdot \frac{1-v^{n+1}}{1-v^{27}} \cdot \frac{1-v^{n+1}}{1-v^{28}} \cdot \frac{1-v^{n+1}}{1-v^{29}} \cdot

Hence the required coefficient is 32.

It is obvious that the particular method adopted in treating the grand determinant made up of 11^2 places employed in the foregoing investigation furnishes or indicates a good practical process for determining 10 out of the 32 numerical coefficients which enter into the expression of Dr. von Gall's covariant $\vec{\epsilon}_4$ as a linear function of the 32 linearly independent covariants of its own deg-order; but, as this calculation possesses no point either of intrinsic theoretical interest or practical importance, I leave it to those who may feel any curiosity on the subject, to go through the calculations necessary to attain that end.

It may be supposed that the long calculations rendered necessary by the quadrinomial form f, attributed to the primitive in the preceding investigation, might have been evaded by using a trinomial form (of which several exist) possessing the same property of causing the two first invariants to vanish, and not less general, inasmuch as containing three independent coefficients in place of four connected by a homogeneous equation; *c. g.* we might assume for the primitive $(0, b, 0, 0, 0, f, 0, 0, i)(x, y)^8$, where the weights of b, f, i are respectively 1, 5, 8.

The quadrinvariant vanishes because no binary combination of 1, 5, 8, with or without repetitions, will make up the required weight 8, and the cubinvariant because no ternary combination of the same will make up the weight 12. It may, however, easily be shown that such form will lead only to a nugatory conclusion, as not supplying the necessary number of arguments (10 at least are wanted) to support the independence of the 10 surviving compound covariants of deg-order 10.4. This may be seen as follows.

The weights of the coefficients of x^4, x^3y, x^2y^2, xy^3, y^4 in a 10.4 covariant are respectively 38, 39, 40, 41, 42. Let us ascertain in how many ways 10 numbers, consisting exclusively of the numbers 1, 5, 8, can be put together to make up these totals. I use the notation $a^\alpha . b^\beta . c^\gamma$ to indicate a sum of α numbers a, β numbers b, and γ numbers c.

Then the sole admissible representations of 38 are $8^4 . 1^6$, $5^7 . 1^3$,

" 39 " $8^3 . 5^2 . 1^5$,

" 40 " $8^2 . 5^4 . 1^4$,

" 41 " $8 . 5^6 . 1^3$,

" 42 " $8^4 . 5 . 1^5$, $5^8 . 1^2$,

i. e. there are only at utmost 7 arguments contained in the expressions for the 10 compounds.

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So, in like manner, if we assumed for the primitive

$$(0,\ b,\ 0,\ 0,\ 0,\ 0,\ g,\ 0,\ i)(x,\ y)^8$$

to find the number of independent arguments possible in a 10.4 covariant, we must ascertain the sum of the numbers of similar representations to the foregoing of the same integers 38, 39, 40, 41, 42, with 10 integers confined to be 1, 6 or 8, and we shall find that the sole representations of that kind are $8^4.1^6$; $8^3.6^3.1^2$; $6^6.1^4$; $8^4.6.1^3$; $8^3.6^3.1^5$; $8.6^5.1^4$, *i. e.* 6 representations in all. In like manner it will be found that all the other trinomial forms of the primitive so taken that the first two invariants are null, will be incapable of yielding as many as 10 arguments to any covariant of deg-order 10.4.* so that the 10 compounds appurtenant to such special form will be bound to be linearly related, and no inference can be drawn from any such assumption. I have reason for believing that the quadrinomial form employed

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* On an exhaustive examination, it will be found that the only trinomial forms of the primitive which will cause the first two invariants to disappear, are those in which the surviving coefficients are

$$b, f, i;\ b, g, i$$
$$a, b, c;\ a, b, d;\ a, c, d;\ b, c, d,$$

or the complementary ones

$$g, d, a;\ h, c, a$$
$$i, h, g;\ i, h, f;\ i, g, f;\ h, g, f,$$

which, of course, are substantially equivalent to the former.

Confining our attention, then, to the upper group, it will readily be seen that the four last will cause not only the quadrinvariant and the cubinvariant, but all the other invariants as well, to vanish. Since, then, it has been shown that the b, f, i; b, g, i forms are insufficient to support the independence of the 10 compound covariants with which the reasoning is concerned, it follows that *no trinomial form* will be adequate to do so.

It may be asked what would have been the effect of using the form in which b, c, d, i are the surviving coefficients, but b, c, d are supposed mutually independent, instead of being subject to the condition employed in the refutation above: on this supposition the quadrinvariant, but not the cubinvariant, will vanish; and an easy calculation will show that of the 32 representations of the covariant of deg-order 10.4 as a product of inferior groundforms there will be only 16 in which the quadrinvariant does not appear as a factor. And, again, it will be found that the number of ways of representing 38, 39, 40, 41, 42, as the sum of 4 numbers, each of which is either 1, 2, 3 or 8 is 29. Hence there would arise a matrix of 16 lines and 29 columns, and to disprove the existence of the 10.4 groundform it would be sufficient to prove that some one of the *complete* minor determinants of this matrix differs from zero. The work involved in dealing with this and the subsequent verificatory matrix of 17 lines and 29 columns would evidently be vastly greater and more liable to error than when (as in the text) we assign the relation between b, c, d so as to make the cubinvariant vanish.

In the absence of the information as to the number of linearly independent 10.4's given by Cayley's rule, the direct mode of refutation would have required the calculation of the 32 compound 10.4's and the problematical one of von Gall for the general form of the Octavic, subject only to the simplification of taking two of the coefficients zero. There would then have remained to show that the leading terms of these 33 forms were linearly connected, which would necessarily imply that the same was true of the 33 entire forms themselves; a colossal task, probably transcending the sphere of human ability to execute.

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in the foregoing investigation is the most convenient and economical, as leading to the simplest calculations of any that could have been employed for the same purpose.

It may be well (by way of confirmation) to determine *à priori* the number of possible arguments that can belong to the 10.4 covariants of the quadrinomial form of $(x, y)^8$ employed in the antecedent investigation. Since c^3 may be replaced by a numerical multiple of bd, it follows that each argument may be brought to a form in which c does not enter at all, or in which it enters only in the first degree. The total possible number (which turns out to be the actual number) of arguments is, consequently, the number of ways in which 38, 39, 40, 41, 42 can be composed with 10 parts each of them 1, 3 or 8 + the number of ways in which 36, 37, 38, 39, 40 can be composed with 9 parts, each of them also 1, 3 or 8. All the possible different compositions of these kinds are exhibited in the annexed table.

$38 = 4.8 + 6.1 = 2.8 + 7.3 + 1.1$	$36 = 3.8 + 3.3 + 3.1$
$39 = 3.8 + 4.3 + 3.1$	$37 = 4.8 + 5.1 = 2.8 + 7.3$
$40 = 4.8 + 5.1 + 1.3 = 2.8 + 8.3$	$38 = 3.8 + 4.3 + 2.1$
$41 = 3.8 + 5.3 + 2.1$	$39 = 4.8 + 1.3 + 4.1$
$42 = 4.8 + 4.1 + 2.3$	$40 = 3.8 + 5.3 + 1.1.$

There are thus 7 + 6 *i. e.* 13 distinct arguments, *i. e.* the number which actually appear distributed among the 10 surviving covariants of deg-order 10.4 as previously shown—it being at the same time remembered that three of the 13 enter as elements of a fixed linear combination into the 10 functions, which are thus virtually functions of only 11 independent arguments.

The method employed in what precedes suggests a mode of calculating in part at least the discriminant of the eighthic in terms of the subordinate groundforms. Thus, suppose we take for our special form, $(0, b, c, d, 0, 0, 0, 0, i)(x, y)^8$ with b, c, d independent.

Then the quadrinvariant will vanish, and there will be no very great effort of calculation required to express the 8 remaining invariants as functions of b, c, d, i.

The discriminant is of the 14th degree and 14 may be made up in 10 (and no more than 10) ways as a sum of numbers each limited to be 3, 4, 5, 6, 7, 8, 9, or 10; as exhibited in the exhaustive table

$14 = 10 + 4 = 9 + 5 = 8 + 6 = 8 + 3 + 3 = 7 + 7 = 7 + 4 + 3 = 6 + 4 + 4$
$= 6 + 5 + 3 = 5 + 5 + 4 = 4 + 4 + 3 + 3.$

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Again the weight of the discriminant is 56, and the number of ways of compounding 56 with 14 numbers each limited to be 1, 2, 3 or 8 is 11, as shown in the exhaustive table

$$\begin{aligned}56 &= 8.6 + 8.1 = 5.8 + 7.2 + 2.1 = 5.8 + 3.3 + 1.2 + 5.1 = 5.8 + 2.3 \\ &+ 3.2 + 4.1 = 5.8 + 1.3 + 5.2 + 3.1 = 5.8 + 7.2 + 2.1 = 4.8 \\ &+ 7.3 + 3.1 = 4.8 + 6.3 + 2.2 + 2.1 = 4.8 + 5.3 + 4.2 + 1.1 \\ &= 4.8 + 4.3 + 8.2 = 3.8 + 10.3 + 1.2\end{aligned}$$

Now there will be no difficulty at all in finding by substitution and multiplication the discriminant of the assumed quantic, say Q, which is in fact the same as the resultant of $\frac{dQ}{dy}$ and $bdy + 2cdy^2 + 3de^2$. Hence there will be 11 equations for determining the coefficients of the 10 invariants of the 14th degree which are products of the inferior invariants (the quadrinvariant excepted): consequently there will be sufficient or more than sufficient equations for the purpose, unless it should (unfortunately and contrary to probability) turn out to be the case that the 10 products, although linear functions of 11 arguments, are expressible as linear functions of only 9 linear functions of those arguments.

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On the Logic of Number

By C. S. Peirce.

Nobody can doubt the elementary propositions concerning number: those that are not at first sight manifestly true are rendered so by the usual demonstrations. But although we see they *are* true, we do not so easily see precisely *why* they are true; so that a renowned English logician has entertained a doubt as to whether they were true in all parts of the universe. The object of this paper is to show that they are strictly syllogistic consequences from a few primary propositions. The question of the logical origin of these latter, which I here regard as definitions, would require a separate discussion. In my proofs I am obliged to make use of the logic of relatives, in which the forms of inference are not, in a narrow sense, reducible to ordinary syllogism. They are, however, of that same nature, being merely syllogisms in which the objects spoken of are pairs or triplets. Their validity depends upon no conditions other than those of the validity of simple syllogism, unless it be that they suppose the existence of singulars, while syllogism does not.

The selection of propositions which I have proved will, I trust, be sufficient to show that all others might be proved with like methods.

Let r be any relative term, so that one thing may be said to be r of another, and the latter r'd by the former. If in a certain system of objects, whatever is r of an r of anything is itself r of that thing, then r is said to be a transitive relative in that system. (Such relatives as "lover of everything loved by —" are transitive relatives.) In a system in which r is transitive, let the q's of anything include that thing itself, and also every r of it which is not r'd by it. Then q may be called a fundamental relative of quantity; its properties being, first, that it is transitive; second, that everything in the system is q of itself, and, third, that nothing is both q of and q'd by anything except itself. The objects of a system having a fundamental relation of quantity are called quantities, and the system is called a system of quantity.

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A system in which quantities may be q's of or q'd by the same quantity without being either q's of or q'd by each other is called multiple;* a system in which of every two quantities one is a q of the other is termed simple.

Simple Quantity.

In a simple system every quantity is either "as great as" or "as small as" every other; whatever is as great as something as great as a third is itself as great as that third, and no quantity is at once as great as and as small as anything except itself.

A system of simple quantity is either continuous, discrete, or mixed. A continuous system is one in which every quantity greater than another is also greater than some intermediate quantity greater than that other. A discrete system is one in which every quantity greater than another is next greater than some quantity (that is, greater than without being greater than something greater than). A mixed system is one in which some quantities greater than others are next greater than some quantities, while some are continuously greater than some quantities.

Discrete Quantity.

A simple system of discrete quantity is either limited, semi-limited, or unlimited. A limited system is one which has an absolute maximum and an absolute minimum quantity; a semi-limited system has one (generally considered a minimum) without the other; an unlimited has neither.

A simple, discrete, system, unlimited in the direction of increase or decrement, is in that direction either infinite or super-infinite. An infinite system is one in which any quantity greater than x can be reached from x by successive steps to the next greater (or less) quantity than the one already arrived at. In other words, an infinite, discrete, simple, system is one in which, if the quantity next greater than an attained quantity is itself attained, then any quantity greater than an attained quantity is attained; and by the class of attained quantities is meant any class whatever which satisfies these conditions. So that we may say that an infinite class is one in which if it is true that every quantity next greater than a quantity of a given class itself belongs to that class, then it is true that every

* For example, in the ordinary algebra of imaginaries two quantities may both result from the addition of quantities of the form $a^2 + b^2 i$ to the same quantity without either being in this relation to the other.

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quantity greater than a quantity of that class belongs to that class. Let the class of numbers in question be the numbers of which a certain proposition holds true. Then, an infinite system may be defined as one in which from the fact that a certain proposition, if true of any number, is true of the next greater, it may be inferred that that proposition if true of any number is true of every greater.

Of a super-infinite system this proposition, in its numerous forms, is untrue.

Semi-infinite Quantity.

We now proceed to study the fundamental propositions of semi-infinite, discrete, and simple quantity, which is ordinary number.

Definitions.

The minimum number is called one.

By $x + y$ is meant, in case $x = 1$, the number next greater than y; and in other cases, the number next greater than $x' + y$, where x' is the number next smaller than x.

By $x \times y$ is meant, in case $x = 1$, the number y, and in other cases $y + x'y$, where x' is the number next smaller than x.

It may be remarked that the symbols $+$ and $\times$ are triple relatives, their two correlates being placed one before and the other after the symbols themselves.

Theorems.

The proof in each case will consist in showing, 1st, that the proposition is true of the number one, and 2d, that if true of the number n it is true of the number $1 + n$, next larger than n. The different transformations of each expression will be ranged under one another in one column, with the indications of the principles of transformation in another column.

1. To prove the associative principle of addition, that

$$(x + y) + z = x + (y + z)$$

whatever numbers x, y, and z, may be. First it is true for $x = 1$; for

$(1 + y) + z$

$= 1 + (y + z)$ by the definition of addition, 2d clause. Second, if true for $x = n$, it is true for $x = 1 + n$; that is, if $(n + y) + z = n + (y + z)$ then $((1 + n) + y) + z = (1 + n) + (y + z)$. For

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$$
\begin{aligned}
&((1+n)+y)+z \\
&=(1+(n+y))+z \quad \text{by the definition of addition:} \\
&=1+((n+y)+z) \quad \text{by the definition of addition:} \\
&=1+(n+(y+z)) \quad \text{by hypothesis:} \\
&=(1+n)+(y+z) \quad \text{by the definition of addition.}
\end{aligned}
$$

2. To prove the commutative principle of addition that

$$x+y=y+x$$

whatever numbers x and y may be. First, it is true for $x=1$ and $y=1$, being in that case an explicit identity. Second, if true for $x=n$ and $y=1$, it is true for $x=1+n$ and $y=1$. That is, if $n+1=1+n$, then $(1+n)+1=1+(1+n)$. For $(1+n)+1$

$$
\begin{aligned}
&=1+(n+1) \quad \text{by the associative principle:} \\
&=1+(1+n) \quad \text{by hypothesis.}
\end{aligned}
$$

We have thus proved that, whatever number x may be, $x+1=1+x$, or that $x+y=y+x$ for $y=1$. It is now to be shown that if this be true for $y=n$, it is true for $y=1+n$; that is, that if $x+n=n+x$, then $x+(1+n)=(1+n)+x$. Now,

$$
\begin{aligned}
&x+(1+n) \\
&=(x+1)+n \quad \text{by the associative principle:} \\
&=(1+x)+n \quad \text{as just seen:} \\
&=1+(x+n) \quad \text{by the definition of addition:} \\
&=1+(n+x) \quad \text{by hypothesis:} \\
&=(1+n)+x \quad \text{by the definition of addition.}
\end{aligned}
$$

Thus the proof is complete.

3. To prove the distributive principle, first clause. The distributive principle consists of two propositions:

$$
\begin{aligned}
&\text{1st,} \quad (x+y)z=xz+yz \\
&\text{2d,} \quad x(y+z)=xy+xz.
\end{aligned}
$$

We now undertake to prove the first of these. First, it is true for $x=1$. For

$$
\begin{aligned}
&(1+y)z \\
&=z+yz \quad \text{by the definition of multiplication:} \\
&=1.z+yz \text{ by the definition of multiplication.}
\end{aligned}
$$

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Second, if true for $x = n$, it is true for $x = 1 + n$; that is, if $(n + y)\, z = nz + yz$, then $((1 + n) + y)\, z = (1 + n)\, z + yz$. For

$$\begin{aligned}
&((1 + n) + y)\, z \\
&= (1 + (n + y))\, z && \text{by the definition of addition:} \\
&= z + (n + y)\, z && \text{by the definition of multiplication:} \\
&= z + (nz + yz) && \text{by hypothesis:} \\
&= (z + nz) + yz && \text{by the associative principle of addition:} \\
&= (1 + n)\, z + yz && \text{by the definition of multiplication.}
\end{aligned}$$

4. To prove the second proposition of the distributive principle, that

$$x\,(y + z) = xy + xz\,.$$

First, it is true for $x = 1$; for

$$\begin{aligned}
&1\,(y + z) \\
&= y + z && \text{by the definition of multiplication:} \\
&= 1y + 1z && \text{by the definition of multiplication.}
\end{aligned}$$

Second, if true for $x = n$, it is true for $x = 1 + n$; that is, if $n\,(y + z) = ny + nz$, then $(1 + n)\,(y + z) = (1 + n)\, y + (1 + n)\, z$. For

$$\begin{aligned}
&(1 + n)\,(y + z) \\
&= (y + z) + n\,(y + z) && \text{by the definition of multiplication:} \\
&= (y + z) + (ny + nz) && \text{by hypothesis:} \\
&= (y + ny) + (z + nz) && \text{by the principles of addition:} \\
&= (1 + n)\, y + (1 + n)\, z && \text{by the definition of multiplication.}
\end{aligned}$$

5. To prove the associative principle of multiplication; that is, that

$$(xy)\, z = x\,(yz),$$

whatever numbers x, y, and z, may be. First, it is true for $x = 1$, for

$$\begin{aligned}
&(1y)\, z \\
&= yz && \text{by the definition of multiplication:} \\
&= 1\,.\,yz && \text{by the definition of multiplication.}
\end{aligned}$$

Second, if true for $x = n$, it is true for $x = 1 + n$; that is, if $(ny)\, z = n\,(yz)$, then $((1 + n)\, y)\, z = (1 + n)\,(yz)$. For

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$$\begin{aligned}
&((1+n)\,y)\,z \\
&= (y + ny)\,z && \text{by the definition of multiplication:} \\
&= yz + (ny)\,z && \text{by the distributive principle:} \\
&= yz + n\,(yz) && \text{by hypothesis:} \\
&= (1+n)\,(yz) && \text{by the definition of multiplication.}
\end{aligned}$$

6. To prove the commutative principle of multiplication: that

$$xy = yx,$$

whatever numbers x and y may be. In the first place, we prove that it is true for $y = 1$. For this purpose, we first show that it is true for $y = 1$, $x = 1$; and then that if true for $y = 1$, $x = n$, it is true for $y = 1$, $x = 1 + n$. For $y = 1$ and $x = 1$, it is an explicit identity. We have now to show that if $n1 = 1n$ then $(1+n)\,1 = 1\,(1+n)$. Now,

$$\begin{aligned}
&(1+n)\,1 \\
&= 1 + n1 && \text{by the definition of multiplication:} \\
&= 1 + 1n && \text{by hypothesis:} \\
&= 1 + n && \text{by the definition of multiplication:} \\
&= 1\,(1+n) && \text{by the definition of multiplication.}
\end{aligned}$$

Having thus shown the commutative principle to be true for $y = 1$, we proceed to prove that if it is true for $y = n$, it is true for $y = 1 + n$: that is, if $xn = nx$, then $x\,(1+n) = (1+n)\,x$. For

$$\begin{aligned}
&(1+n)\,x \\
&= x + nx && \text{by the definition of multiplication:} \\
&= x + xn && \text{by hypothesis:} \\
&= 1x + xn && \text{by the definition of multiplication:} \\
&= x1 + xn && \text{as already seen:} \\
&= x\,(1+n) && \text{by the distributive principle.}
\end{aligned}$$

Discrete Simple Quantity Infinite in both directions.

A system of number infinite in both directions has no minimum, but a certain quantity is called *one*, and the numbers as great as this constitute a partial system of semi-infinite number, of which this one is a minimum. The definitions of addition and multiplication require no change, except that the *one* therein is to be understood in the new sense.

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To extend the proofs of the principles of addition and multiplication to unlimited number, it is necessary to show that if true for any number $(1+n)$ they are also true for the next smaller number n. For this purpose we can use the same transformations as in the second clauses of the former proof; only we shall have to make use of the following lemma.

If $x+y=x+z$, then $y=z$ whatever numbers x, y, and z, may be. First this is true in case $x=1$, for then y and z are both next smaller than the same number. Therefore, neither is smaller than the other, otherwise it would not be next smaller to $1+y=1+z$. But in a simple system, of any two different numbers one is smaller. Hence, y and z are equal. Second, if the proposition is true for $x=n$, it is true for $x=1+n$. For if $(1+n)+y=(1+n)+z$, then by the definition of addition $1+(n+y)=1+(n+z)$; whence it would follow that $n+y=n+z$, and, by hypothesis, that $y=z$. Third, if the proposition is true for $x=1+n$, it is true for $x=n$. For if $n+y=n+z$, then $1+n+y=1+n+z$, because the system is simple. The proposition has thus been proved to be true of 1, of every greater and of every smaller number, and therefore to be universally true.

An inspection of the above proofs of the principles of addition and multiplication for semi-infinite number will show that they are readily extended to doubly infinite number by means of the proposition just proved.

The number next smaller than one is called naught, 0. This definition in symbolic form is $1+0=1$. To prove that $x+0=x$, let x' be the number next smaller than x. Then,

$$
\begin{aligned}
& x+0 \\
&= (1+x')+0 && \text{by the definition of } x' \\
&= (1+0)+x' && \text{by the principles of addition:} \\
&= 1+x' && \text{by the definition of naught:} \\
&= x && \text{by the definition of } x'.
\end{aligned}
$$

To prove that $x0=0$. First, in case $x=1$, the proposition holds by the definition of multiplication. Next, if true for $x=n$, it is true for $x=1+n$. For

$$
\begin{aligned}
& (1+n)\,0 \\
&= 1.\,0+n.\,0 && \text{by the distributive principle:} \\
&= 1.\,0+0 && \text{by hypothesis:} \\
&= 1.\,0 && \text{by the last theorem:} \\
&= 0 && \text{as above.}
\end{aligned}
$$

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Third, the proposition, if true for $x = 1 + n$ is true for $x = n$. For, changing the order of the transformations,

$$1.0 + 0 = 1.\ 0 = 0 = (1 + n)\,0 = 1.\ 0 + n.0.$$

Then by the above lemma, $n.\ 0 = 0$, so that the proposition is proved.

A number which added to another gives naught is called the negative of the latter. To prove that every number greater than naught has a negative. First, the number next smaller than naught is the negative of one; for, by the definition of addition, one plus this number is naught. Second, if any number n has a negative, then the number next greater than n has for its negative the number next smaller than the negative of n. For let m be the number next smaller than the negative of n. Then $n + (1 + m) = 0$.

But $n + (1 + m)$
$= (n + 1) + m$ by the associative principle of addition.
$= (1 + n) + m$ by the commutative prineiple of addition.

So that $(1 + n) + m = 0$. *Q. E. D.* Hence, every number greater than 0 has a negative, and naught is its own negative.

To prove that $(-x)\,y = -(xy)$. We have

$0 = x + (-x)$	by the definition of the negative:
$0 = 0y = (x + (-x))\,y$	by the last proposition but one:
$0 = xy + (-x)\,y$	by the distributive principle:
$-(xy) = (-x)\,y$	by the definition of the negative.

The negative of the negative of a number is that number. For $x + (-x) = 0$. Whence by the definition of the negative $x = -(-x)$.

Limited Discrete Simple Quantity.

Let such a relative term, c, that whatever is a c of anything is the only c of that thing, and is a c of that thing only, be called a relative of simple correspondence. In the notation of the logic of relatives,

$$c\check{c} -\!\prec 1,\quad \check{c}c -\!\prec 1.$$

If every object, s, of a class is in any such relation c, with a number of a semi-infinite discrete simple system, and if, further, every number smaller than a number c'd by an s is itself c'd by an s, then the numbers c'd by the s's are

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said to count them, and the system of correspondence is called a count. In logical notation, putting g for as great as, and n for a positive integral number,

$$s \prec \breve{c}n \quad \breve{g}cs \prec cs .$$

If in any count there is a maximum counting number, the count is said to be finite, and that number is called the number of the count. Let $[s]$ denote the number of a count of the s's, then

$$[s] \prec cs \quad \bar{g}cs \prec [s] .$$

The relative "identical with" satisfies the definition of a relative of simple correspondence, and the definition of a count is satisfied by putting "identical with" for c, and "positive integral number as small as x" for s. In this mode of counting, the number of numbers as small as x is x.

Suppose that in any count the number of numbers as small as the minimum number, one, is found to be n. Then, by the definition of a count, every number as small as n counts a number as small as one. But, by the definition of one there is only one number as small as one. Hence, by the definition of single correspondence, no other number than one counts one. Hence, by the definition of one, no other number than one counts any number as small as one. Hence, by the definition of the count, one is, in every count, the number of numbers as small as one.

If the number of numbers as small as x is in some count y, then the number of numbers as small as y is in some count x. For if the definition of a simple correspondence is satisfied by the relative c, it is equally satisfied by the relative c'd by.

Since the number of numbers as small as x is in some count y, we have, c being some relative of simple correspondence,

1st. Every number as small as x is c'd by a number.

2d. Every number as small as a number that is c of a number as small as x is itself c of a number as small as x.

3d. The number y is c of a number as small as x.

4th. Whatever is not as great as a number that is c of a number as small as x is not y.

Now let c_1 be the converse of c. Then the converse of c_1 is c; whence, since c satisfies the definition of a relative of simple correspondence, so also does c_1. By the 3d proposition above, every number as small as y is as small as a number that is c of a number as small as x. Whence, by the 2d proposition,

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every number as small as y is c of a number as small as x; and it follows that every number as small as y is c_1'd by a number. It follows further that every number c_1 of a number as small as y is c_1 of something c_1'd by (that is, c_1 being a relative of simple correspondence, is identical with) some number as small as x. Also, "as small as" being a transitive relative, every number as small as a number c of a number as small as y is as small as x. Now by the 4th proposition y is as great as any number that is c of a number as small as x, so that what is not as small as y is not c of a number as small as x; whence whatever number is c'd by a number not as small as y is not a number as small as x. But by the 2d proposition every number as small as x not c'd by a number not as small as y is c'd by a number as small as y. Hence, every number as small as x is c'd by a number as small as y. Hence, every number as small as a number c_1 of a number as small as y is c_1 of a number as small as y. Moreover, since we have shown that every number as small as x is c_1 of a number as small as y, the same is true of x itself. Moreover, since we have seen that whatever is c_1 of a number as small as y is as small as x, it follows that whatever is not as great as a number c_1 of a number as small as y is not as great as a number as small as x; *i. e.* ("as great as" being a transitive relative) is not as great as x, and consequently is not x. We have now shown—

1st, that every number as small as y is c_1'd by a number;

2d, that every number as small as a number that is c_1 of a number as small as y is itself c_1 of a number as small as y;

3d, that the number x is c_1 of a number as small as y; and

4th, that whatever is not as great as a number that is c_1 of a number as small as y is not x.

These four propositions taken together satisfy the definition of the number of numbers as small as y counting up to x.

Hence, since the number of numbers as small as one cannot in any count be greater than one, it follows that the number of numbers as small as any number greater than one cannot in any count be one.

Suppose that there is a count in which the number of numbers as small as $1 + m$ is found to be $1 + n$, since we have just seen that it cannot be 1. In this count, let m' be the number which is c of $1 + n$, and let n' be the number which is c'd by $1 + m$. Let us now consider a relative, e, which differs from c only in excluding the relation of m' to $1 + n$ as well as the relation of $1 + m$ to n'

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and in including the relation of m' to n'. Then e will be a relative of single correspondence; for c is so, and no exclusion of relations from a single correspondence affects this character, while the inclusion of the relation of m' to n' leaves m' the only e of n' and an e of n' only. Moreover, every number as small as m is e of a number, since every number except $1+m$ that is c of anything is e of something, and every number except $1+m$ that is as small as $1+m$ is as small as m. Also, every number as small as a number e'd by a number is itself e'd by a number; for every number c'd is e'd except $1+m$, and this is greater than any number e'd. It follows that e is the basis of a mode of counting by which the numbers as small as m count up to n. Thus we have shown that if in any way $1+m$ counts up to $1+n$, then in some way m counts up to n. But we have already seen that for $x=1$ the number of numbers as small as x can in no way count up to other than x. Whence it follows that the same is true whatever the value of x.

If every S is a P, and if the P's are a finite lot counting up to a number as small as the number of S's, then every P is an S. For if, in counting the P's, we begin with the S's (which are a part of them), and having counted all the S's arrive at the number n, there will remain over no P's not S's. For if there were any, the number of P's would count up to more than n. From this we deduce the validity of the following mode of inference:

Every Texan kills a Texan,
Nobody is killed by but one person,
Hence, every Texan is killed by a Texan,

supposing Texans to be a finite lot. For, by the first premise, every Texan killed by a Texan is a Texan killer of a Texan. By the second premise, the Texans killed by Texans are as many as the Texan killers of Texans. Whence we conclude that every Texan killer of a Texan is a Texan killed by a Texan, or, by the first premise, every Texan is killed by a Texan. This mode of reasoning is frequent in the theory of numbers.

NOTE.—It may be remarked that when we reason that a certain proposition, if false of any number, is false of some smaller number, and since there is no number (in a semi-limited system) smaller than every number, the proposition must be true, our reasoning is a mere logical transformation of the reasoning that a proposition, if true for n, is true for $1+n$, and that it is true for 1.

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On the Remainder of Laplace's Series.

By Emory McClintock, *Milwaukee, Wis.*

The remainder of Lagrange's series has been given by Popoff and Zolotareff* in the form $\frac{1}{n!}\mathrm{D}^n\int_z(x\phi t+z-t)^n f't\,.\,dt$, where $y=z+x\phi y$, and $\mathrm{D}=\frac{d}{dz}$.

The corresponding expression for the remainder of Laplace's series, where $y=f(z+x\phi y)$, is $r_n=\frac{1}{n!}\mathrm{D}^n\int_{fz}^{\infty}(x\phi t+z-f^{-1}t)^n f't\,.\,dt$.

To prove this, it is only necessary to perform one of the n differentiations indicated, by the usual rule for the differentiation of definite integrals with variable limits. In this way we find that

$$r_n=r_{n-1}-\frac{1}{n!}x^n\mathrm{D}^{n-1}(\phi fz)^n\mathrm{D}fz,$$

whence, if $m=n-1$,

$$r_m=\frac{1}{m+1!}x^{m+1}\mathrm{D}^m(\phi fz)^{m+1}\mathrm{D}fz+r_{m+1}.$$

Since $r_0=fy-ffz$, we have at once, by successive substitution,

$$fy=ffz+x\phi fz\mathrm{D}fz+\frac{1}{2!}x^2\mathrm{D}(\phi fz)^2\mathrm{D}fz+\ldots+\frac{1}{n!}x^n\mathrm{D}^{n-1}(\phi fz)^n\mathrm{D}fz+r_n.$$

Comparing this result with Laplace's theorem, we see that we have in r_n an expression for the remainder after $n+1$ terms.

If $fz=z$, or, in other words, if $y=z+x\phi y$, we have M. Popoff's expression for the remainder in Lagrange's theorem. The above method of proof resembles in principle that by which Zolotareff proves the latter expression.

It must not be thought that the reasoning here employed constitutes a proof of Laplace's theorem, for evidence is still needed that $r_\infty=0$ when the series is convergent. In other words, the series is not thus proved to be necessarily the true development of fy. Suppose $s_n=\frac{x^{n+1}-1}{1-x}$, so that

$$s_0=-1=x+x^2+x^3+\ldots+x^n+s_n;$$

this would not furnish the true development of -1 in terms of x.

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* See Williamson's *Integral Calculus*, 3d ed.; *Jahrbuch über die Fortschritte der Math.* VIII; these referring to Popoff (*Comptes Rendus*, 1861, pp. 795-8,) and Zolotareff (*Nouv. Annales*, 3d series, XV, 429-3).

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The consent of the family of the late Professor Benjamin Peirce has been kindly given to the publication in the *American Journal of Mathematics*, of his valuable and unique memoir on Linear Associative Algebra, of which only a small number of copies in lithograph were taken in the author's lifetime, for distribution among his friends. This publication will, it is believed, supply a want which has been long and widely felt, and bring within the reach of the general mathematical public a work which may almost be entitled to take rank as the *Principia* of the philosophical study of the laws of algebraical operation.

Linear Associative Algebra.

A Memoir read before the National Academy of Sciences in Washington, 1870.

By Benjamin Peirce.

With Notes and Addenda, by C. S. Peirce, Son of the Author.

1. Mathematics is the science which draws necessary conclusions.

This definition of mathematics is wider than that which is ordinarily given, and by which its range is limited to quantitative research. The ordinary definition, like those of other sciences, is objective; whereas this is subjective. Recent investigations, of which quaternions is the most noteworthy instance, make it manifest that the old definition is too restricted. The sphere of mathematics is here extended, in accordance with the derivation of its name, to all demonstrative research, so as to include all knowledge strictly capable of dogmatic teaching. Mathematics is not the discoverer of laws, for it is not induction; neither is it the framer of theories, for it is not hypothesis; but it is the judge over both, and it is the arbiter to which each must refer its claims; and neither law can rule nor theory explain without the sanction of mathematics. It deduces from a law all its consequences, and develops them into the suitable form for comparison with observation, and thereby measures the strength of the argument from observation in favor of a proposed law or of a proposed form of application of a law.

Mathematics, under this definition, belongs to every enquiry, moral as well as physical. Even the rules of logic, by which it is rigidly bound, could not be deduced without its aid. The laws of argument admit of simple statement, but they must be curiously transposed before they can be applied to the living speech and verified by observation. In its pure and simple form the syllogism cannot be directly compared with all experience, or it would not have required an

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Analysis of Inference. It must be understood that all the principle stages in which reasoning is developed. The mathematical part of the mathematical process in the establishment of the law. Of course, whatever is a large part that they have been quite unnoticed in the mathematical—which may not have been an error to the advantage of philosophy—but in the case where many and complex the latter. But in many cases as in all cases of mental philosophy and most of the practical branches of natural history, the deduction is an immediate and of such simple character that it is of no practical use to separate the mathematical part in and to put it to isolated document.

2. The practical branches of mathematics are as various as the subjects to which they belong and each subject of physical enquiry has its appropriate mathematics. In every form of material manifestation there is a correspondence of form of human thought so that the human mind is as wide in its range of thought as the physical universe in which it thinks. The two are wonderfully matched. But where there is a great diversity of physical appearance there is often a close resemblance in the processes of deduction. It is important therefore to separate the intellectual work from the external form. Symbols must be adopted which may serve for the embodiment of forms of argument without being trammeled by the conditions of external representation or special interpretation. The words of common language are usually unfit for this purpose, so that other symbols must be adopted, and mathematics treated by such symbols is called *algebra*. Algebra, then, is formal mathematics.

3. All relations are either qualitative or quantitative. Qualitative relations can be considered by themselves without regard to quantity. The algebra of such enquiries may be called logical algebra, of which a fine example is given by *Boole*.

Quantitative relations may also be considered by themselves without regard to quality. They belong to arithmetic and the corresponding algebra is the *common* or arithmetical algebra.

In all other algebras both relations must be combined, and the algebra must conform to the character of the relations.

4. The symbols of an algebra, with the laws of combination, constitute its *language*; the methods of using the symbols in the drawing of inferences is its *art*; and their interpretation is its *scientific application*. This three-fold analysis of algebra is adopted from President Hill, of Harvard University, and is made the basis of a division into books.

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BOOK I.*

THE LANGUAGE OF ALGEBRA.

5. The language of algebra has its alphabet, vocabulary, and grammar.

6. The symbols of algebra are of two kinds: one class represent its fundamental conceptions and may be called its *letters*, and the other represent the relations or modes of combination of the letters and are called *the signs*.

7. The *alphabet* of an algebra consists of its letters; the *vocabulary* defines its signs and the elementary combinations of its letters; and the *grammar* gives the rules of composition by which the letters and signs are united into a complete and consistent system.

The Alphabet.

8. Algebras may be distinguished from each other by the number of their independent fundamental conceptions, or of the letters of their alphabet. Thus an algebra which has only one letter in its alphabet is a *single* algebra; one which has two letters is a *double* algebra; one of three letters a *triple* algebra; one of four letters a *quadruple* algebra, and so on.

This artificial division of the algebras is cold and uninstructive like the artificial Linnean system of botany. But it is useful in a preliminary investigation of algebras, until a sufficient variety is obtained to afford the material for a natural classification.

Each fundamental conception may be called a *unit;* and thus each unit has its corresponding letter, and the two words, unit and letter, may often be used indiscriminately in place of each other, when it cannot cause confusion.

9. The present investigation, not usually extending beyond the sextuple algebra, limits the demand of the algebra for the most part to six letters; and the six letters, i, j, k, l, m and n, will be restricted to this use except in special cases.

10. *For any given letter another may be substituted,* provided a new letter represents a combination of the original letters of which the replaced letter is a necessary component.

For example, any combination of two letters, which is entirely dependent for its value upon both of its components, such as their sum, difference, or product, may be substituted for either of them.

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*Only this book was ever written. [C. S. P.]

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The principle of the substitution of letters is extremely important, and is a necessary result of the analytic character of the present investigation, and will be found an indispensable aid in many future researches. It will be the province to analyze an algebra relative to its simplest and most general forms and compare it with other algebras. It will then be possible to establish a corresponding nomenclature of such forms as may really be found representative.

There is no danger in dealing with the signs of the components of the same unit, and the same letter, out of the change of the original meaning we may be easily reminded by the mark of the operation.

12. In making the substitution of letters the original letter will be preserved with the addition of a subscript number.

Thus a in the series a more may successively be substituted by a_1, a_2 etc. In the final forms the subscript numbers can be omitted, and they may be omitted at any period of the investigation when it will not produce confusion.

It will be practically found that these subscript numbers need scarcely ever be written. They pass through the mind as a mere ideal protection from error—a substitution, but disappear from the writing with the same facility with which those evanescent chemical compounds, which are essential to the theory of transformation, escape the eye of the observer.

12. A *pure* algebra is one in which every letter is connected by some indeterminate relation with every other letter.

13. When the letters of an algebra can be separated into two groups, which are mutually independent, it is a *mixed algebra*. It is mixed even when there are letters common to the two groups, provided those which are not common to the two groups are mutually independent. Were an algebra employed for the simultaneous discussion of distinct classes of phenomena, such as those of sound and light, and were the peculiar units of each class to have their appropriate letters, but were there no recognized dependence of the phenomena upon each other, so that the phenomena of each class might have been submitted to independent research, the one algebra would be actually a mixture of two algebras, one appropriate to sound, the other to light.

It may be farther observed that when, in such a case as this, the component algebras are identical in form, they are reduced to the case of one algebra with two diverse interpretations.

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The Vocabulary.

14. Letters which are not appropriated to the alphabet of the algebra * may be used in any convenient sense. But it is well to employ *the small letters* for expressions of common algebra, and *the capital letters* for those of the algebra under discussion.

There must, however, be exceptions to this notation; thus the letter D will denote the derivative of an expression to which it is applied, and Σ the summation of cognate expressions, and other exceptions will be mentioned as they occur. Greek letters will generally be reserved for angular and functional notation.

15. The three symbols $\jmath$, Θ, and Θ will be adopted with the signification

$$\jmath = \sqrt{-1}$$

Θ = the ratio of circumference to diameter of circle = 3.1415926536

Θ = the base of Naperian logarithms = 2.7182818285,

which gives the mysterious formula

$$\jmath^{-\jmath} = \sqrt{\Theta^{\Theta}} = 4.810477381.$$

16. All the signs of common algebra will be adopted; but any signification will be permitted them which is not inconsistent with their use in common algebra; so that, if by any process an expression to which they refer is reduced to one of common algebra, they must resume their ordinary signification.

17. The sign $=$, which is called that of equality, is used in its ordinary sense to denote that the two expressions which it separates are the same whole, although they represent different combinations of parts.

18. The signs $>$ and $<$ which are those of inequality, and denote "more than" or "less than" in quantity, will be used to denote the relations of a whole to its part, so that the symbol which denotes the part shall be at the vertex of the angle, and that which denotes the whole at its opening. This involves the proposition that the smaller of the quantities is included in the class expressed by the larger. Thus

$$B < A \text{ or } A > B$$

denotes that A is a whole of which B is a part, so that all B is A.†

* See § 9.

† The formula in the text implies, also, that some A is not B. [C. S. P.]

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If the usual algebra had originated in qualitative, instead of quantitative, investigations, the use of the symbols might easily have been reversed; for it seems that all conceptions involved in A must also be involved in B, so that B is more than A in the sense that it involves more ideas.

The combined expression

$$B > C < A$$

denotes that there are quantities expressed by C which belong to the class A and also to the class B. It implies, therefore, that some B is A and that some A is B.* The intermediate C might be omitted if this were the only proposition intended to be expressed, and we might write

$$B > < A.$$

In like manner the combined expression

$$B < C > A$$

denotes that there is a class which includes both A and B.† which proposition might be written

$$B < > A.$$

19. A vertical mark drawn through either of the preceding signs reverses its signification. Thus

$$A \neq B$$

denotes that B and A are essentially different wholes;

$$A \not> B \text{ or } B \not< A$$

denotes that all B is not A,‡ so that if they have only quantitative relations, they must bear to each other the relation of

$$A = B \text{ or } A < B.$$

20. The sign $+$ is called *plus* in common algebra and denotes *addition*. It may be retained with the same name, and the process which it indicates may be called addition. In the simplest cases it expresses a mere mixture, in which

* This, of course, supposes that C does not vanish. [C. S. P.]

† The universe will be such a class unless A or B is the universe. [C. S. P.]

‡ The general interpretation is rather that either A and B are identical or that some B is not A. [C. S. P.]

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the elements preserve their mutual independence. If the elements cannot be mixed without mutual action and a consequent change of constitution, the mere union is still expressed by the sign of addition, although some other symbol is required to express the character of the mixture as a peculiar compound having properties different from its elements. It is obvious from the simplicity of the union recognized in this sign, that the order of the admixture of the elements cannot affect it; so that it may be assumed that

$$A + B = B + A$$

and

$$(A + B) + C = A + (B + C) = A + B + C.$$

21. The sign $-$ is called *minus* in common algebra, and denotes *subtraction*. Retaining the same name, the process is to be regarded as the reverse of addition; so that if an expression is first added and then subtracted, or the reverse, it disappears from the result; or, in algebraic phrase, it is *canceled*. This gives the equations

$$A + B - B = A - B + B = A$$

and

$$B - B = 0.$$

The sign minus is called the negative sign in ordinary algebra, and any term preceded by it may be united with it, and the combination may be called a *negative term*. This use will be adopted into all the algebras, with the provision that the derivation of the word negative must not transmit its interpretation.

22. The sign $\times$ may be adopted from ordinary algebra with the name of the sign of *multiplication*, but without reference to the meaning of the process. The result of multiplication is to be called the *product*. The terms which are combined by the sign of multiplication may be called *factors*; the factor which precedes the sign being distinguished as the *multiplier*, and that which follows it being the *multiplicand*. The words multiplier, multiplicand, and product, may also be conveniently replaced by the terms adopted by Hamilton, of *facient*, *faciend*, and *factum*. Thus the equation of the product is

multiplier $\times$ multiplicand = product; *or* facient $\times$ faciend = factum.

When letters are used, the sign of multiplication can be *omitted* as in ordinary algebra.

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23. When an expression used as a factor in certain combinations gives a product which vanishes, it may be called in those combinations a *nilfactor*. Where as the multiplier it produces vanishing products it is *nilfacient*, but where it is the multiplicand of such a product it is *nilfaciend*.

24. When an expression used as a factor in certain combinations overpowers the other factors and is itself the product, it may be called an *idemfactor*. When in the production of such a result it is the multiplier, it is *idemfacient*, but when it is the multiplicand it is *idemfaciend*.

25. When an expression raised to the square or any higher power vanishes, it may be called *nilpotent*; but when, raised to a square or higher power, it gives itself as the result, it may be called *idempotent*.

The defining equation of nilpotent and idempotent expressions are respectively $A^n = 0$, and $A^n = A$; but with reference to idempotent expressions, it will always be assumed that they are of the form

$$A^2 = A,$$

unless it be otherwise distinctly stated.

26. *Division* is the reverse of multiplication, by which its results are verified. It is the process for obtaining one of the factors of a given product when the other factor is given. It is important to distinguish the position of the given factor, whether it is facient or faciend. This can be readily indicated by combining the sign of multiplication, and placing it before or after the given factor just as it stands in the product. Thus when the multiplier is the given factor, the correct equation of division is

$$\text{quotient} = \frac{\text{dividend}}{\text{divisor} \times}$$

and the equation of verification is

$$\text{divisor} \times \text{quotient} = \text{dividend}.$$

But when the multiplicand is the given factor, the equation of division is

$$\text{quotient} = \frac{\text{dividend}}{\times \text{divisor}}$$

and the equation of verification is

$$\text{quotient} \times \text{divisor} = \text{dividend}.$$

27. Exponents may be introduced just as in ordinary algebra, and they may even be permitted to assume the forms of the algebra under discussion.

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There seems to be no necessary restriction to giving them even a wider range and introducing into one algebra the exponents from another. Other signs will be defined when they are needed.

The definition of the fundamental operations is an essential part of the vocabulary, but as it is subject to the rules of grammar which may be adopted, it must be reserved for special investigation in the different algebras.

The Grammar.

28. Quantity enters as a form of thought into every inference. It is always implied in the syllogism. It may not, however, be the direct object of inquiry; so that there may be logical and chemical algebras into which it only enters accidentally, agreeably to § 1. But where it is recognized, it should be received in its most general form and in all its variety. The algebra is otherwise unnecessarily restricted, and cannot enjoy the benefit of the most fruitful forms of philosophical discussion. But while it is thus introduced as a part of the formal algebra, it is *subject to every degree and kind of limitation in its interpretation.*

The free introduction of quantity into an algebra does not even involve the reception of its unit as one of the independent units of the algebra. But it is probable that without such a unit, no algebra is adapted to useful investigation. It is so admitted into quaternions, and its admission seems to have misled some philosophers into the opinion that quaternions is a triple and not a quadruple algebra. This will be the more evident from the form in which quaternions first present themselves in the present investigation, and in which the unit of quantity is not distinctly recognizable without a transmutation of the form.*

29. The introduction of quantity into an algebra naturally carries with it, not only the notation of ordinary algebra, but likewise many of the rules to which it is subject. Thus, when a quantity is a factor of a product, it has the

* Hamilton's total exclusion of the imaginary of ordinary algebra from the calculus as well as from the interpretation of quaternions will not probably be accepted in the future development of this algebra. It evinces the resources of his genius that he was able to accomplish his investigations under these trammels. But like the restrictions of the ancient geometry, they are inconsistent with the generalizations and broad philosophy of modern science. With the restoration of the ordinary imaginary, quaternions becomes Hamilton's biquaternions. From this point of view, all the algebras of this research would be called bi-algebras. But with the ordinary imaginary is involved a vast power of research, and the distinction of names should correspond; and the algebra which loses it should have its restricted nature indicated by such a name as that of a *semi-algebra.*

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same influence whether it be facient or faciend, so that with the notation of § 14, there is the equation

$$Aa = aA,$$

and in such a product, the quantity a may be called the *coefficient*.

In like manner, terms which only differ in their coefficients, may be added by adding their coefficients: thus,

$$(a \pm b)A = aA \pm bA = Aa \pm Ab = A(a \pm b).$$

30. The exceeding simplicity of the conception of an equation involves the identity of the equations

$$A = B \text{ and } B = A$$

and the substitution of B for A in every expression, so that

$$MA \pm C = MB \pm C,$$

or that, *the members of an equation may be mutually transposed or simultaneously increased or decreased or multiplied or divided by equal expressions.*

31. How far the principle of § 16 limits the extent within which the ordinary symbols may be used, cannot easily be decided. But it suggests limitations which may be adopted during the present discussion, and leave an ample field for curious investigation.

The distributive principle of multiplication may be adopted; namely, the principle that the product of an algebraic sum of factors into or by a common factor, is equal to the corresponding algebraic sum of the individual products of the various factors into or by the common factor; and it is expressed by the equations

$$(A \pm B)C = AB \pm BC.$$
$$C(A \pm B) = CA \pm CB.$$

32. *The associative principle of multiplication* may be adopted; namely, that the product of successive multiplications is not affected by the order in which the multiplications are performed, provided there is no change in the relative position of the factors; and it is expressed by the equations

$$ABC = (AB)C = A(BC).$$

This is quite an important limitation, and the algebras which are subject to it will be called *associative*.

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33. The principle that the value of a product is not affected by the relative position of the factors is called *the commutative principle*, and is expressed by the equation

$$AB = BA.$$

This principle is *not* adopted in the present investigation.

34. An algebra in which every expression is reducible to the form of an algebraic sum of terms, each of which consists of a single *letter* with a quantitative coefficient, is called *a linear algebra.** Such are all the algebras of the present investigation.

35. Wherever there is a limited number of independent conceptions, a linear algebra may be adopted. For a combination which was not reducible to such an algebraic sum as those of linear algebra, would be to that extent independent of the original conceptions, and would be an independent conception additional to those which were assumed to constitute the elements of the algebra.

36. An algebra in which there can be complete interchange of its independent units, without changing the formulae of combination, is a *completely symmetrical algebra;* and one in which there may be a partial interchange of its units is *partially symmetrical.* But the term symmetrical should not be applied, unless the interchange is more extensive than that involved in the distributive and commutative principles. An algebra in which the interchange is effected in a certain order which returns into itself is a *cyclic algebra.*

Thus, quaternions is a cyclic algebra, because in any of its fundamental equations, such as

$$\begin{aligned} i^2 &= -1 \\ ij &= -ji = k \\ ijk &= -1 \end{aligned}$$

there can be an interchange of the letters in the order i, j, k, i, each letter being changed into that which follows it. The double algebra in which

$$\begin{aligned} i^2 &= i, \quad ij = i \\ j^2 &= j, \quad ji = j \end{aligned}$$

* In the various algebras of De Morgan's "Triple Algebra," the distributive, associative and commutative principles were all adopted, and they were all linear. [De Morgan's algebras are "semi-algebras." See Cambridge Phil. Trans., viii, 241.] [C. S. P.]

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is cyclic because the letters are interchangeable in the order i, j, i. But neither of these algebras is commutative.

37. When an algebra can be reduced to a form in which all the letters are expressed as powers of some one of them, it may be called a *potential algebra*. If the powers are all squares, it may be called *quadratic*; if they are cubes, it may be called *cubic*; and similarly in other cases.

Linear Associative Algebra.

38. *All the expressions of an algebra are distributive, whenever the distributive principle extends to all the letters of the alphabet.*

For it is obvious that in the equation

$$(i+j)(k+l) = ik + jk + il + jl$$

each letter can be multiplied by an integer, which gives the form

$$(ai + bj)(ck + dl) = acik + bejk + adil + bdjl,$$

in which a, b, c and d are integers. The integers can have the ratios of any four real numbers, so that by simple division they can be reduced to such real numbers. Other similar equations can also be formed by writing for a and b, a_1 and b_1, or for c and d, c_1 and d_1, or by making both these substitutions simultaneously. If then the two first of these new equations are multiplied by $\jmath$ and the last by -1; the sum of the four equations will be the same as that which would be obtained by substituting for a, b, c and d, $a + \jmath a_1$, $b + \jmath b_1$, $c + \jmath c_1$ and $d + \jmath d_1$. Hence a, b, c and d may be any numbers, real or imaginary, and in general whatever mixtures A, B, C and D may represent of the original units under the form of an algebraic sum of the letters i, j, k, &c., we shall have

$$(A + B)(C + D) = AC + BC + AD + BD,$$

which is the complete expression of the distributive principle.

39. *An algebra is associative whenever the associative principle extends to all the letters of its alphabet.*

For if

$$A = \Sigma(ai) = ai + a_1 j + a_2 k + \&c.$$
$$B = \Sigma(bi) = bi + b_1 j + b_2 k + \&c.$$
$$C = \Sigma(ci) = ci + c_1 j + c_2 k + \&c.$$

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it is obvious that

$$AB = \Sigma(ab_1ij)$$
$$BC = \Sigma(bc_1ij)$$
$$(AB)C = \Sigma(ab_1c_2ijk) = A(BC) = ABC$$

which is the general expression of the associative principle.

40. *In every linear associative algebra, there is at least one idempotent or one nilpotent expression.*

Take any combination of letters at will and denote it by A. Its square is generally independent of A, and its cube may also be independent of A and A^2. But the number of powers of A that are independent of A and of each other, cannot exceed the number of letters of the alphabet; so that there must be some least power of A which is dependent upon the inferior powers. The mutual dependence of the powers of A may be expressed in the form of an equation of which the first member is an algebraic sum, such as

$$\Sigma_m(a_m A^m) = 0.$$

All the terms of this equation that involve the square and higher powers of A may be combined and expressed as BA, so that B is itself an algebraic sum of powers of A, and the equation may be written

$$BA + a_1 A = (B + a_1)A = 0.$$

It is easy to deduce from this equation successively

$$(B + a_1)\, A^n = 0$$
$$(B + a_1)\, B = 0$$
$$\left(-\frac{B}{a_1}\right)^2 = -\frac{B}{a_1}$$

so that $-\frac{B}{a_1}$ is an idempotent expression. But if a_1 vanishes, this expression becomes infinite, and instead of it we have the equation

$$B^2 = 0$$

so that B is a nilpotent expression.

41. When there is *an idempotent expression* in a linear associative algebra, it can be assumed as one of the independent units, and be represented by *one of the letters of the alphabet;* and it may be called *the basis.*

The remaining units can be so selected as to be separable into four distinct groups.

With reference to the basis, the units of the first group are idemfactors; those of the second group are idemfaciend and nilfacient; those of the third group are idemfacient and nilfaciend; and those of the fourth group are nilfactors.

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First. The possibility of the selection of all the remaining units as idemfaciend or nilfaciend is easily established. For if i is the idempotent base, its definition gives

$$i^2 = i.$$

The product by the basis of another expression such as A may be represented by B, so that

$$iA = B,$$

which gives

$$iB = i^2A = iA = B$$
$$i(A - B) = iA - iB = B - B = 0.$$

whence it appears that B is idemfaciend and $A - B$ is nilfaciend. In other words, A is divided into two parts, of which one is idemfaciend and the other is nilfaciend; but either of these parts may be wanting, so as to leave A wholly idemfaciend or wholly nilfaciend.

Secondly. The still farther subdivision of these portions into idemfacient and nilfacient is easily shown to be possible by this same method, with the mere reversal of the relative position of the factors. Hence are obtained the required four groups.

The basis itself may be regarded as belonging to the first group.

42. Any algebraic sum of the letters of a group is an expression which belongs to the same group, and may be called *factorially homogeneous.*

43. *The product of two factorially homogeneous expressions, which does not vanish, is itself factorially homogeneous, and its faciend name is the same as that of its facient, while its facient name is the same as that of its faciend.*

Thus, if A and B are, each of them, factorially homogeneous, they satisfy the equations

$$i(AB) = (iA)B,$$
$$(AB)i = A(Bi),$$

which shows that the nature of the product as a faciend is the same as that of the facient A, and its nature as a facient is the same as that of the faciend B.

44. *Hence, no product which does not vanish can be commutative unless both its factors belong to the same group.*

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45. *Every product vanishes, of which the facient is idemfacient while the faciend is nilfaciend; or of which the facient is nilfacient while the faciend is idemfaciend.*

For in either case this product involves the equation

$$AB = (Ai)B = A(iB) = 0.$$

46. The combination of the propositions of §§ 43 and 45 is expressed in the following form of a multiplication table. In this table, each factor is expressed by two letters, of which the first denotes its name as a faciend and the second as a facient. The two letters are d and n, of which d stands for *idem* and n for *nil*. The facient is written in the left hand column of the table and the faciend in the upper line. The character of the product, when it does not vanish, is denoted by the combination of letters, or when it must vanish, by the zero, which is written upon the same line with the facient and in a column under the faciend.

	dd	*dn*	*nd*	*nn*
dd	*dd*	*dn*	0	0
dn	0	0	*dd*	*dn*
nd	*nd*	*nn*	0	0
nn	0	0	*nd*	*nn*

47. It is apparent from the inspection of this table, that *every expression* which belongs to the second or third group is nilpotent.

48. It is apparent that *all commutative products which do not vanish are restricted to the first and fourth groups.*

49. It is apparent that every continuous product which does not vanish, has the same faciend name as its first facient, and the same facient name as its last faciend.

50. Since the products of the units of a group remain in the group, they cannot serve as the bond for uniting different groups, which are the necessary conditions of a pure algebra. Neither can the first and fourth groups be connected by direct multiplication, because the products vanish. *The first and fourth groups, therefore, require for their indissoluble union into a pure algebra that there should be units in each of the other two groups.*

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51. In an algebra which has more than two independent units, it cannot happen that all the units except the base belong to the second or to the third group. For in this case, each unit taken with the base would constitute a double algebra, and there would be no bond of connection to prevent their separation into distinct algebras.

52. *The units of the fourth group are subject to the same determination, as if they constituted an algebra of the nonions.* There may be in this group an idempotent or a nilpotent unit. If there is an idempotent unit, it can be adopted as *the basis of the group, through which the group can be considered into subsidiary groups.*

The idempotent unit of the fourth group can even be made the basis of the whole algebra, and the first, second and third groups will respectively become the fourth, third and second groups for the new basis.

53. *When the first group comprises any units except the basis, there is besides the basis another idempotent expression, or there is a nilpotent expression.* By a process similar to that of § 40 and a similar argument, it may be shown that for any expression A, which belongs to the first group, there is some least power which can be expressed by means of the basis and the inferior powers in the form of an algebraic sum. This condition may be expressed by the equation

$$\Sigma_n (a_n A^n) + bi = 0.$$

If then h is determined by the ordinary algebraic equation

$$\Sigma_n (a_n h^n) + b = 0,$$

and if

$$A_1 = A - hi$$

is substituted for A, an equation is obtained between the powers of A_1 from which an idempotent expression, B, or else a nilpotent expression, can be deduced precisely as in § 40.*

54. *When there is a second idempotent unit in the first group, the basis can be changed so as to free the first group from this second idempotent unit.*

Thus if i is the basis, and if j is the second idempotent unit of the first group, the basis can be changed to

* The equation in h may have no algebraic solution, in which case the new idempotent or nilpotent would not be a direct algebraic function of i and A. [C. S. P.]

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$$i_1 = i - j;$$

and with this new basis, j passes from the first to the fourth group. For

First, the new basis is idempotent, since

$$i_1^2 = (i-j)^2 = i^2 - 2ij + j^2 = i - j = i_1;$$

and *secondly*, the idempotent unit j passes into the fourth group, since

$$i_1 j = (i-j)j = ij - j^2 = j - j = 0,$$
$$j i_1 = j(i-j) = ji - j^2 = j - j = 0.$$

55. *With the preceding change of basis, expressions may pass from idemfacient to nilfacient, or from idemfaciend to nilfaciend, but not the reverse.*

For *first*, if A is nilfacient with reference to the original basis, it is also, by § 45, nilfacient with reference to the new basis; or if it is nilfaciend with reference to the original basis, it is nilfaciend with reference to the new basis.

Secondly, all expressions which are idemfacient with reference to the original basis, can, by the process of § 41, be separated into two portions with reference to the new basis, of which portions one is idemfacient and the other is nilfacient; so that the idemfacient portion remains idemfacient, and the remainder passes from being idemfacient to being nilfacient. The same process may be applied to the faciends with similar conclusions.

56. It is evident, then, that each group* can be reduced so as not to contain more than one idempotent unit, which will be its basis. In the groups which bear to the basis the relations of second and third groups, there are only nilpotent expressions.

57. *In a group or an algebra which has no idempotent expression, all the expressions are nilpotent.*

Take any expression of this group or algebra and denote it by A. If nq power of A vanished, there must be, as shown in § 40, some equation between the powers of A of the form

$$\Sigma_m a_m A^m = 0,$$

in which a_1 must vanish, or else there would be an idempotent expression as is shown in § 40, which is contrary to the present hypothesis. If then m_0 denote

* That is, the first group as well as each of the subsidiary groups of § 52. [C. S. P.]

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the exponent of the next power of A that entered into the equation, and $m_k - 1$ the exponent of the highest power that occurred in it, the whole number of terms of the equation would be at most $k - 1$. If now the equation were multiplied successively by A and by each of its powers as far as that of which the exponent is $m_k - 1$, the highest exponent would be m_k, the number of new equations which would be thus obtained. If moreover

$$B = A^{m_k}$$

then the highest power of A introduced into these equations would be

$$A^{m_k - 1 + m_k} = A^{m_k} A^{m_k - 1} = B^2 A^{m_k - 1}.$$

The whole number of powers of A contained in the equations would be $m_k k - 1$, and $k - 1$ of these would always be integral powers of B, and there would remain $m_k - 1$ of the number which were not integral powers of B. There will therefore always be equations to eliminate all the powers of A that were not integral powers of B and will leave an equation between the integral powers of B; and this will generally include the first power of B. From the equation so obtained expressions can be obtained by the process of § 40, which is contrary to the hypothesis of the proposition.

Therefore it cannot be the case that there is any equation such as here assumed; and therefore there can be no expression which is nilpotent. The few cases of peculiar doubt can readily be solved as they occur; but they always must involve the possibility of an equation between fewer powers of B than those in the equation in A.*

58. *When an expression is nilpotent, all its powers which do not vanish are mutually independent.*

Let A be the nilpotent expression, of which the n^{th} power is the highest which does not vanish. There cannot be any equation between these powers of the form

$$\Sigma_m a_m A^m = 0.$$

* In saying that the equation in B will generally include the first power of B, he intends to waive the question of whether this always happens. For, he reasons, if this is not the case then the equation in B is to be treated just as the equation in A has been treated, and such repetitions of the process must ultimately produce an equation from which either an idempotent expression could be found, or else A would be proved nilpotent. [C. S. P.]

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For if m_0 were the exponent of the lowest power of A in this equation, the multiplication of the equation by the $(n - m_0)^{\text{th}}$ power of A reduces it to

$$a_{m_0} A^n = 0, \quad a_{m_0} = 0,$$

that is, the m_0^{th} power of A disappears from the equation, or there is no least power of A in the equation, or, more definitely, there is no such equation.

59. *In a group or an algebra which contains no idempotent expression, any expression may be selected as the basis; but one is preferable which has the greatest number of powers which do not vanish.* All the powers of the basis which do not vanish may be adopted as independent units and represented by the letters of the alphabet.

A nilpotent group or algebra may be said to be of the same order with the number of powers of its basis that do not vanish, provided the basis is selected by the preceding principle. Thus, if the squares of all its expressions vanish, it is of the *first order;* if the cubes all vanish and not all the squares, it is *of the second order*, and so on.

60. It is obvious that *in a nilpotent group whose order equals the number of letters which it contains, all the letters except the basis may be taken as the successive powers of the basis.*

61. In a nilpotent group, every expression, such as A, has some least power that is nilfacient with reference to any other expression, such as B, and which corresponds to what may be called *the facient order of B relatively to A*; and in the same way, there is some least power of A which is nilfaciend with reference to B, and which corresponds to *the faciend order of B relatively to A.* When the facient and faciend orders are treated of irrespective of any especial reference, *they must be referred to the base.*

The facient order of a product which does not vanish, is not higher than that of its facient; and the faciend order is not higher than that of its faciend.

62. After the selection of the basis of a nilpotent group, some one from among the expressions which are independent of the basis may be selected by the same method by which the basis was itself selected, *which, together with all its powers that are independent of the basis, may be adopted as new letters;* and again, from the independent expressions which remain, *new letters may be selected by the same process, and so on until the alphabet is completed.* In making these selections, regard should be had to the factorial orders of the products.

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63. In every nilpotent group, *the highest order of any letter which is independent of the basis can be assumed to be as low as the number of letters which are independent of the basis.*

Thus, if the number of letters which are independent of the basis is denoted by n', and if n is the order of the group and for the present purpose it is sufficient to regard n' as being less than n, it is evident that any expression A, with its successive products by the powers of the basis i, as high as the n'^{th}, and the powers of the basis which do not vanish, cannot all be independent of one another; so that there must be an equation of the form

$$\sum_{1}^{n'} a_n i^n + \sum_{1}^{n'} b_n i^n A = 0 .$$

Accordingly, it is easy to see that there is always a value of A_1 of the form

$$A_1 = A - \sum_{1}^{n'} k_n i^n$$

which will give

$$i^{n'} A_1 = 0 ,$$

which corresponds to the condition of this section.

There is a similar condition which holds in every selection of a new letter by the method of the preceding section.

64. *In a nilpotent group, the order of which is less by unity than the number of letters, the letter which is independent of the basis and its powers may be so selected that its product into the basis shall be equal to the highest power of the basis which does not vanish, and that its square shall either vanish or shall also be equal to the highest power of the basis that does not vanish.* Thus, if the basis is i, and if the order of the algebra is n, and if j is the remaining letter, it is obvious, from § 63, that j might have been assumed such that

$$ij = 0 ,$$

which gives

$$jji = ij^2 = 0 ;$$

and therefore,

$$\begin{aligned} ji &= ai^n + bj , \\ j^2 &= a'i^n + bj , \\ 0 &= ji^{n+1} = bji^n = b^n ji = b , \\ ji &= ai^n , \\ j^2 i &= aji^n = 0 = bj^2 = b' , \\ j^3 &= a'i^n : \end{aligned}$$

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so that if

$$h=\left(\frac{a^{i}}{a^{j}}\right)^{\frac{1}{i-j}},\quad k=\left(\frac{a^{in-1}}{a^{n}}\right)^{\frac{1}{n}}$$

$$j_1=\frac{j}{k},\qquad i_1=\frac{i}{h},$$

we have

$$j_1 i_1 = i_1^{n}=j_1^{i},$$

and i_1 and j_1 can be substituted for i and j, which conforms to the proposition enunciated.

It must be observed, however, that the analysis needs correction when the group is of the second order.

65. *In a nilpotent group of the first order, the sign of a product is merely reversed by changing the order of its factors.* Thus, if

$$A^{2}=B^{2}=(A+B)^{2}=0$$

it follows by development, that

$$(A+B)^{2}=A^{2}+AB+BA+B^{2}=AB+BA=0$$
$$BA=-AB,$$

which is the proposition enunciated.

66. *In general, in any nilpotent group of the n^{th} order, if $(A^{s},\ B^{t})$ denotes the sum of all possible products of the form*

$$A^{p}B^{q}\ A^{p'}B^{q'}\ A^{p''}B^{q''}\ \ldots$$

in which

$$\Sigma p=s,\quad \Sigma q=t,$$

and if

$$s+t=n+1,$$

it will be found that

$$(A^{s},\ B^{t})=0.$$

For since

$$(A+xB)^{n+1}=0$$

whatever be the value of x, the multiplier of each power of x must vanish, which gives the proposed equation

$$(A^{s},\ B^{t})=0.$$

67. *In the first group of an algebra, having an idempotent basis, all the expressions except the basis may be assumed to be nilpotent.* For, by the same argument as that of §53, any equation between an expression and its successive powers and the basis must involve an equation between another expression which is

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easily defined and its successive powers without including the basis. But it follows from the argument of § 57, that such an equation indicates a corresponding idempotent expression; whereas it is here assumed that, in accordance with § 66, each group has been brought to a form which does not contain any other idempotent expression than the basis. It must be, therefore, that all the other expressions are nilpotent.

65. *No product of expressions in the first group of an algebra having an idempotent basis, contains a term which is a multiple of the basis.*

For, assume the equation

$$AB = -xi + C.$$

in which A, B and C are nilpotents of the orders m, n and p, respectively. Then,

$$0 = A^{m-1}B = -xA^m + A^mC$$
$$A^mC = xA^m$$
$$0 = A^mC^{p-1} = xA^mC^{p-1} = x^2A^mC^{p-2} = x^{p-1}A^m = x.$$

that is, the term $-xi$ vanishes from the product AB.

66. It follows, from the preceding section, that *if the idempotent basis were taken away from the first group of which it is the basis, the remaining letters of the first group would constitute by themselves a nilpotent algebra.*

Conversely, *any nilpotent algebra may be converted into an algebra with an idempotent basis, by the simple annexation of a letter idemfacient and idemfacient with reference to every other.**

70. However incapable of interpretation the nilfactorial and nilpotent expressions may appear, they are obviously an essential element of the calculus of linear algebras. Unwillingness to accept them has retarded the progress of discovery and the investigation of quantitative algebras. But the idempotent basis seems to be equally essential to actual interpretation. The purely nilpotent algebra may therefore be regarded as an ideal abstraction, which requires the introduction of an idempotent basis, to give it any position in the real universe. In the subsequent investigations, therefore, the purely nilpotent algebras must be regarded as the first steps towards the discovery of algebras of a higher degree resting upon an idempotent basis.

* That every such algebra must be a pure one is plain, because the algebra (a_1) is so. [C. S. P.]

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71. Sufficient preparation is now made for the

INVESTIGATION OF SPECIAL ALGEBRAS.

The following notation will be adopted in these researches. Conformably with § 9, the letters of the alphabet will be denoted by i, j, k, l, m and n. To these letters will also be respectively assigned the numbers 1, 2, 3, 4, 5 and 6. Moreover, their coefficients in an algebraic sum will be denoted by the letters a, b, c, d, e and f. Thus, the product of any two letters will be expressed by an algebraic sum, and below each coefficient will be written in order the numbers which are appropriate to the factors. Thus,

$$jl = a_{24}\, i + b_{24}\, j + c_{24}\, k + d_{24}\, l + e_{24}\, m + f_{24}\, n,$$

while

$$lj = a_{42}\, i + b_{42}\, j + c_{42}\, k + d_{42}\, l + e_{42}\, m + f_{42}\, n.$$

In the case of a square, only one number need be written below the coefficient, thus

$$k^2 = a_3\, i + b_3\, j + c_3\, k + d_3\, l + e_3\, m + f_3\, n.$$

The investigation simply consists in the determination of the values of the coefficients, corresponding to every variety of linear algebra; and the resulting products can be arranged in a tabular form which may be called the multiplication-table of the algebra. Upon this table rests all the peculiarity of the calculus. In each of the algebras, it admits of many transformations, and much corresponding speculation. The basis will be denoted by i.

72. The distinguishing of the successive cases by the introduction of numbers will explain itself, and is an indispensable protection from omission of important steps in the discussion.

SINGLE ALGEBRA.

Since in a single algebra there is only one independent unit, it requires no distinguishing letter. It is also obvious that there can be no single algebra which is not associative and commutative. Single algebra has, however, two cases:

[1], when its unit is idempotent;
[2], when it is nilpotent.

[1]. The defining equation of this case is

$$i^2 = i.$$

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This algebra may be called (a_1) and its multiplication table is *

$$(a_1) \quad \begin{array}{c|c} & i \\ \hline i & i \\ \hline \end{array}$$

[2]. The defining equation of this case is

$$i^2 = 0.$$

This algebra may be called (b_1) and its multiplication table is †

$$(b_1) \quad \begin{array}{c|c} & i \\ \hline i & 0 \\ \hline \end{array}$$

DOUBLE ALGEBRA.

There are two cases of double algebra:

[1], when it has an idempotent expression;
[2], when it is nilpotent.

[1]. The defining equation of this case is

$$i^2 = i.$$

By §§ 41 and 50, there are two cases:

[1²], when the other unit belongs to the first group;
[12], when it is of the second group.

The hypothesis that the other unit belongs to the third group is a virtual repetition of [12].

[1²]. The defining equations of this case are

$$ij = ji = j.$$

It follows from §§ 67 and 69, that there is a double algebra derived from (b_1) which may be called (a_2), of which the multiplication table is ‡

* This algebra may be represented by $i = A : A$ in the logic of relatives. See Addenda. [C. S. P.]
† This algebra takes the form $i = A : B$. in the logic of relatives. [C. S. P.]
‡ This algebra may be put in the form $i = A : A + B : B$. $j = A : B$. [C. S. P.]

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(a_3)	i	j
i	i	j
j	j	0

[12]. The defining equations of this case are, by § 41,

$$ij = j,\ ji = 0;$$

whence, by § 46,

$$j^2 = 0.$$

A double algebra is thus formed, which may be called (b_3), of which the multiplication table is *

(b_3)	i	j
i	i	j
j	0	0

[2]. The defining equation of this case is

$$i^n = 0,$$

in which n is the least power of i which vanishes. There are two cases:

[21], when $n = 3$;
[2²], when $n = 2$.

[21]. The defining equation of this case is

$$i^3 = 0,$$

and by § 60,

$$i^2 = j.$$

This gives a double algebra which may be called (c_3), its multiplication table being †

* This algebra may be put in the form $i = A : A$, $j = A : B$. [C. S. P.]
† In relative form, $i = A : B + B : C$, $j = A : C$. [C. S. P.]

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(e_{ij})	i	j
i	j	0
j	0	0

[2^2]. The defining equations of this case are

$$i^2 = j^2 = 0,$$

and it follows from §§ 64 and 65 that

$$ij = ji = 0,$$

so that there is no pure algebra in this case.*

TRIPLE ALGEBRA.

There are two cases:

[1], when there is an idempotent basis;
[2], when the basis is nilpotent.

[1]. The defining equation of this case is

$$i^3 = i.$$

There are, by §§ 41, 50 and 51, three cases:

[1^3], when j and k are both in the first group;
[12], when j is in the first, and k in the second group;
[13], when j is in the second, and k in the third group.

The case of j being in the first, and k in the third group, is a virtual repetition of [12].

[1^3]. The defining equations of this case are

$$ij = ji = j, \quad ik = ki = k.$$

* This case takes the form $i = A.B,\ j = C:D$. [C. S. P.]

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It follows from §§ 67 and 69, that the only algebra of this case may be derived from (e_4); it may be called (a_3), and its multiplication table is *

(a_3)	i	j	k
i	i	j	k
j	j	k	0
k	k	0	0

[12]. The defining equations of this case are

$$ji = ij = j, \quad ik = k, \quad ki = 0;$$

whence, by §§ 46 and 67,

$$j^2 = k^2 = kj = 0, \quad jk = c_{13}k,$$
$$j^2k = 0 = c_{23}jk = c_{23}^2k = c_{23} = jk,$$

and there is no pure algebra in this case.†

[13]. The defining equations of this case are

$$ij = j, \quad ki = k, \quad ji = ik = 0;$$

whence, by § 46,

$$j^2 = k^2 = kj = 0, \quad jk = a_{23}i,$$
$$jkj = 0 = a_{23}j = a_{23} = jk,$$

and there is no pure algebra in this case.‡

[2]. The defining equation of this case is

$$i^n = 0,$$

in which n is the lowest power of i that vanishes.

There are three cases:

[21], when $n = 4$;
[2^2], when $n = 3$;
[23], when $n = 2$.

* In relative form, $i = A : A + B : B + C : C$, $j = A : B + B : C$, $k = A : C$. [C. S. P.]

† That is to say, i and j by themselves form the algebra a_3, and i and k by themselves constitute the algebra b_1, while the products of j and k vanish. Thus, the three letters are not indissolubly bound together into one algebra. In relative form, this case is, $i = A : A + B : B$, $j = A : B$, $k = A : C$. [C. S. P.]

‡ In relative form, $i = A : A + D : D$, $j = A : B$, $k = C : D$. [C. S. P.]

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[21]. The defining equation of this case is

$$i^2 = 0,$$

and by § 60

$$i^2 = j, \quad i^3 = k.$$

This gives a triple algebra which may be called (b_1), the multiplication table being*

(b_1)	i	j	k
i	j	k	0
j	k	0	0
k	0	0	0

[2^2]. The defining equation of this case is

$$i^2 = 0,$$

and by §§ 59 and 64, observing the exception,

$$i^2 = j, \quad ik = 0.$$
$$ki = b_n j. \quad k^2 = b_n j.$$

There is no pure algebra when b_n vanishes,† and there are two cases:

[$2^2 1$], when b_2 does not vanish;
[2^2], when b_2 vanishes.

[$2^2 1$]. The defining equation of this case can, without loss of generality, be reduced to

$$k^2 = j.$$

This gives a triple algebra which may be called (c_3), the multiplication table being‡

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* In relative form, $i = A:B + B:C + C:D$. $j = A:C + B:D$. $k = A:D$. [C. S. P.]
† This case takes the relative form, $i = A:B + B:C$, $j = A:C$. $k = b_n A:D + D:C$. [C. S. P.]
‡ In relative form, $i = A:B + B:C$, $j = A:C$, $k = a.\ A:B + A:D + D:C$. [C. S. P.]

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(e_3)	i	j	k
i	j	0	0
j	0	0	0
k	aj	0	j

An interesting special example of this case is afforded by $a = -2$, when

$$\begin{aligned} i(k+i) &= -j \\ (k+i)\,i &= j \\ (k+i)^2 &= 0, \end{aligned}$$

so that $k+i$ might be substituted for k, and in this form, the multiplication table of this algebra, which may be called (e'_3), is *

(e'_3)	i	j	k
i	j	0	j
j	0	0	0
k	$-j$	0	0

* In relative form, $i = A:B+B:C$, $j = A:C$, $k = -A:B+B:C+A:D+D:C$.

When $a = +2$, the algebra equally takes the form (e'_3), on substituting $k-i$ for k. On the other hand, provided a is neither 2 nor -2, the algebra may be put in the form

(e''_3)	i	j	k
i	0	0	$-bj$
j	0	0	0
k	$b^{-1}j$	0	0

To effect the transformation, we write $a = -b - \frac{1}{b}$ and substitute $i + bk$ and $i + \frac{1}{b}k$ for i and k, and $\left(b - \frac{1}{b}\right)j$ for j. Thus the algebra (e_3) has two distinct and intransmutable species, (e'_3) and (e''_3). [C. S. P.]

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[2,2]. The defining equations of the unit are

$$i^2 = -1,$$

and i_B may be replaced by any multiple of i by a real number except 0. Any two units i_B, i_C may be chosen for the j, k units in the following

	i	j	k
i	j	k	0
j	0	0	0
k	j	0	0

In this case

$$i - i\,i = 1,$$
$$1 - i^2 = 1,$$
$$i - i^3 = 2i,$$

so that $i - I$ may be substituted for i, and in this form the multiplication table is

	1	i	j	k
1	1	i	j	k
i	i	0	k	0
j	j	$-k$	0	0
k	k	0	0	0

[2,3]. The defining equations of this case are

$$i^2 = j^2 = k^2 = 0,$$

and by the principles of §§ 2,2 and 2,3, it may be assumed that

$$ij = -ji = -ik = ki = 0,$$
$$jk = -kj = i.$$

---

* In matrix form, $i = B \cdot C$, $j = A \cdot C$, $k = A \cdot B$. This is the algebra of quaternions in its typical form, $i^2 = k^2$.

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We thus get a triple algebra which may be called (e_3), its multiplication table being*

(e_3)	i	j	k
i	0	0	0
j	0	0	i
k	0	$-i$	0

QUADRUPLE ALGEBRA.

There are two cases:

[1], when there is an idempotent basis;
[2], when the base is nilpotent.

[1]. The defining equation of this case is

$$i^2 = i.$$

There are six cases:

[1^4], when j, k, and l, are all in the first group;
[12], when j and k are in the first, and l in the second group;
[13], when j is in the first, and k and l in the second group;
[14], when j is in the first, k in the second, and l in the third group;
[15], when j and k are in the second, and l in the third group;
[16], when j is in the second, k in the third, and l in the fourth group.

The other cases are excluded by §§ 50 and 51, or are obviously virtual repetitions of those which are given.

[1^3]. The defining equations of this case are

$$ij = ji = j, \quad ik = ki = k, \quad il = li = l,$$

and from §§ 60 and 69, the algebras (b_3), (c_3), (d_3), and (e_3), give quadruple algebras which may be named respectively (a_4), (b_4), (c_4), and (d_4), their multiplication tables being

* In relative form, $i = .1 : D$. $j = .1 : B - C : D$. $k = .1 : C + B : D$. This is the algebra of alternate numbers. [C. S. P.]

a_1	i	j	k	l
i	i	j	k	l
j	j	k	l	0
k	k	l	0	0
l	l	0	0	0

b_1	i	j	k	l
i	i	j	k	l
j	j	k	0	0
k	k	0	0	0
l	l	ak	0	k

c_1	i	j	k	l
i	i	j	k	l
j	j	k	0	0
k	k	0	0	0
l	l	k	0	0

d_1	i	j	k	l
i	i	j	k	l
j	j	0	0	0
k	k	0	0	j
l	l	0	$-j$	0

The special case c_1 gives a corresponding special case of f_{12} which may be called h_1, of which the multiplication table is

h_1	i	j	k	l
i	i	j	k	l
j	j	k	0	k
k	k	0	0	0
l	l	$-k$	0	0

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The second form of (d_2) gives a corresponding second form of (e_4), of which the multiplication table is

(e_4)	i	j	k	l
i	i	j	k	l
j	j	0	0	0
k	k	0	0	0
l	l	k	0	0

[12]. The defining equations of this case are

$$ij = ji = j, \quad ik = ki = k, \quad il = l, \quad li = 0,$$

and it follows from §§ 67 and 69, that (e_3) gives

$$j^2 = k, \quad jk = kj = k^2 = 0,$$

and from § 46,

$$lj = lk = l^2 = 0, \quad jl = d_{24}l, \quad kl = d_{34}l;$$

whence

$$j^2l = kl = d_{24}jl = d_{34}^2l,$$
$$jkl = d_{24}^2jl = d_{34}^3l = 0 = d_{24} = jl = kl,$$

and there is no pure algebra in this case.*

[13]. The defining equations of this case are

$$ij = ji = j, \quad ik = k, \quad il = l, \quad ki = li = 0,$$

which give by §§ 46 and 67

$$0 = j^2 = k^2 = kl = lk = l^2 = kj = lj;$$

and it may be assumed that

$$jk = l, \text{ whence } jl = 0.$$

This gives a quadruple algebra which may be called (e_4), its multiplication table being †

* In relative form, $i = A : A + B : B + C : C + D : D$, $j = A : B + B : C$, $k = A : C$, $l = D : C$. [C. S. P.]

† In relative form, $i = A : A + B : B$, $j = A : B$, $k = B : C$, $l = A : C$. [C. S. P.]

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(e_4)	i	j	k	l
i	i	j	k	l
j	j	0	l	0
k	0	0	0	0
l	0	0	0	0

[14]. The defining equations of this case are

$$ij = ji = j. \quad ik = k. \quad li = l. \quad ki = il = 0;$$

which give, by §§ 46 and 67,

$$\begin{gathered} 0 = j^3 = jl = kj = k^2 = lk = l^2, \\ jk = c_{23}k, \quad lj = d_{41}l. \quad kl = a_{34}i + b_{34}j, \\ 0 = j^2k = c_{23}jk = c_{23}^2k = c_{23}jk, \\ 0 = lj^2 = d_{41}^2lj = d_{41}lj = d_{41}lj, \\ 0 = jkl = a_{34}j = a_{34}. \end{gathered}$$

and b_{34} cannot be permitted to vanish,* so that it does not lessen the generality to assume

$$kl = j.$$

This gives a quadruple algebra which may be called (f_4), its multiplication table being†

(f_4)	i	j	k	l
i	i	j	k	0
j	j	0	0	0
k	0	0	0	j
l	l	0	0	0

* For then the algebra would split up into three double algebras. [C. S. P.]

† In relative form, $i = A:A + B:B$. $j = A:B$. $k = A:C$. $l = C:B$. [C. S. P.]

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[15]. The defining equations of this case are

$$ij = j, \quad ik = k, \quad li = l, \quad ji = ki = il = 0,$$

which give, by § 46,

$$\begin{gathered} 0 = j^2 jk = kj = k^2 = lj = lk = l^2, \\ jl = a_{24} i, \quad kl = a_{34} i, \\ 0 = jlj = a_{24} j = a_{34} = jl, \\ 0 = klk = a_{34} k = a_{34} = kl, \end{gathered}$$

and there is no pure algebra in this case.*

[16]. The defining equations of this case are

$$ij = j, \quad ki = k, \quad ji = ik = il = li = 0,$$

which give, by § 46,

$$\begin{gathered} 0 = j^2 = k^2 = kl = lj, \\ jk = a_{23} i, \quad jl = b_{24} j, \quad kj = d_{32} l, \quad lk = c_{43} k, \quad l^2 = d_4 l, \\ jkj = a_{23} j = d_{32} b_{24} j, \quad jlk = a_{23} b_{24} i = a_{23} c_{43} i, \quad jl^2 = b_{24}^2 j = b_{24} d_4 j, \\ kjk = a_{23} k = c_{43} d_{32} k, \quad kjl = d_{32} d_4 l = b_{24} d_{32} l, \\ lkj = d_{32} l_4 l = c_{43} d_{32} l, \quad l^2 k = c_{43}^2 k = c_{43} d_4 k, \quad a_{23} = b_{24} d_{32}, \\ 0 = a_{23}(c_{43} - b_{24}) = b_{24}(b_{24} - d_{24}) = d_{32}(b_{24} - d_4) = d_{32}(c_{43} - d_4) = c_{43}(c_{43} - d_4). \end{gathered}$$

There are two cases:

[161], when d_{32} does not vanish;
[162], when d_{32} vanishes.

[161]. The defining equation of this case can be reduced to

$$d_{32} = 1,$$

which gives

$$a_{23} = b_{24} = c_{43} = d_4.$$

There are two cases:

[161^1], when d_4 does not vanish;
[1612], when d_4 vanishes.

[161^1]. The defining equation of this case can be reduced to

$$d_4 = 1,$$

which gives

$$jk = i, \quad jl = j, \quad lk = k, \quad l^2 = l;$$

* In relative form, $i = A : A$, $j = A : B$, $k = A : C$, $l = D : A$. There are three double algebras of the form (b_4). [C. S. P.]

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and there is a quadruple algebra which may be called (g_4), its multiplication table being

(g_4)	i	j	k	l
i	i	j	0	0
j	0	0	i	j
k	k	l	0	0
l	0	0	k	l

This is a form of *quaternions*.*

[1612]. The defining equation of this case is

$$d_4 = 0,$$

which gives

$$jk = jl = lk = l^2 = 0.$$

---

*In relative form, $i = A:A$, $j = A:B$, $k = B:A$, $l = B:B$. This algebra exhibits the general system of relationship of individual relatives, as is shown in my paper in the ninth volume of the Memoirs of the American Academy of Arts and Sciences. In a space of four dimensions, a vector may be determined by means of its rectangular projections on two planes such that every line in the one is perpendicular to every line in the other. Call these planes the A-plane and the B-plane, and let r be any vector. Then, ir is the projection of r upon the A-plane, and kr is its projection upon the B-plane. Let each direction in the A-plane be considered as to correspond to a direction in the B-plane in such a way that the angle between two directions in the A-plane is equal to the angle between the corresponding directions in the B-plane. Then, jr is that vector in the A-plane which corresponds to the projection of r upon the B-plane, and kr is that vector in the B-plane which corresponds to the projection of r upon the A-plane.

Professor Peirce showed that we may take i_1, j_1, k_1, as three such mutually perpendicular vectors in ordinary space, that $i = \frac{1}{2}\ 1 - ji_1 - k_1$, $j = \frac{1}{2}\ j - ji_1 + k_1$, $k = \frac{1}{2}\ -j_1 - ji_1$, $l = \frac{1}{2}\ 1 - ji_1$. [See, also, Spottiswoode, Proceedings of the London Mathematical Society, iv, 156. Cayley, in his Memoir on the Theory of Matrices 1858, had shown how a quaternion may be represented by a dual matrix.] Thus i, j, k, l, have all zero tensors, and j and k are vectors. In the general expression of the algebra, $q = xi + yj + zk + wl$, if $x + w = 1$ and $yz = x - x^2$, we have $q^2 = q$; if $x = -w = \sqrt{-yz}$, then $q^2 = 0$. The expression $i + l$ represents scalar unity, since it is the universal identifactor. We have, also, $Sj = \frac{1}{2}\ x + w\ \ i + l$, $Vq = \frac{1}{2}\ x - w\ \ i + yj + zk + \frac{1}{2}\ w - x\ \ l$. $Tq = \sqrt{xw - yz}\ \ i + l$.

The resemblance of the multiplication table of this algebra to the symbolical table of 146 merits attention. [C. S. P.]

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and there is a quadruple algebra which may be called (h_4), its multiplication table being*

(h_4)	i	j	k	l
i	i	j	0	0
j	0	0	0	0
k	k	l	0	0
l	0	0	0	0

[162]. The defining equation of this case is

$$d_{32} = 0,$$

which gives

$$a_{23} = 0,$$

and there can be no pure algebra for it.†

[2]. The defining equation of this case is

$$i^n = 0.$$

There are four cases: [21], when $n = 5$;
[2^2], when $n = 4$;
[23], when $n = 3$;
[24], when $n = 2$.

[21]. The defining equation of this case is

$$i^5 = 0,$$

and by § 60, $\quad i^3 = j, \quad i^2 = k, \quad i^4 = l.$

This gives a quadruple algebra which may be called (i_4), its multiplication table being‡

---

* In relative form, $i = A:A$, $j = A:B$, $k = C:A$, $l = C:B$. [C. S. P.]

† In this case, $i = A:A$, $l = d_4(B:B + C:C)$, $j = A:B$ or $= A:D$, $k = C:A$ or $= E:A$. [C. S. P.]

‡ In relative form, $i = A:B + B:C + C:D + D:E$, $j = A:C + B:D + C:E$, $k = A:D + B:E$, $l = A:E$. [C. S. P.]

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[25] The defining equation of this table is

$$b = i$$

and by § 59

$$a = i, \quad c = i$$

Thus the only [illegible] in this table are

[26] The defining equation of this table is

$$c = i.$$

and by § 59

$$a = j$$

and it may be assumed from the principle of § 13 that

$$ik = i,$$

which gives

$$jk = i.$$

---

*In either of these algebras, $i = A \cdot B + B \cdot C + C \cdot D$, $j = A \cdot C + B \cdot D$, $k = A \cdot D$; and in j_n, $l = A \cdot E + E \cdot D + A \cdot C$, while in k, $l = A \cdot C$. [C. S. P.]

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There are two cases: [231], when $il = k$;
[232], when $il = 0$.

[231]. The defining equation of this case is

$$il = k,$$

which gives

$jl = i^2 l = ik = 0,$
$ki = a_{31} i + b_{31} j + c_{31} k + d_{31} l,$
$0 = iki = a_{31} j + d_{31} k, \quad a_{31} = 0, \quad d_{31} = 0, \quad ki = b_{31} j + c_{31} k.$

So, because $ik^2 = 0, \quad k^2 = b_{32} j + c_{32} k,$

and because $ikl = 0, \quad kl = b_{34} j + c_{34} k, \quad kj = kii = c_{31} ki = b_{31} c_{31} j + c_{31}^2 k.$
$0 = kji = c_{31}^2 ki, \quad c_{31} = 0 = kj,$
$ili = ki = b_{31} j, \quad li = b_{21} i + b_{41} j + c_{41} k, \quad lj = li^2 = (b_{21} + b_{31} c_{41}) j,$
$0 = k^3 = c_{32} k^2 = c_3, \quad ilk = k^2 = b_{32} j, \quad lk = b_{21} i + b_{42} j + c_{42} k,$
$l^2 = a_4 i + b_4 j + c_4 k + d_4 l, \quad 0 = l^3 = a_4 k + c_4 kl + d_4 l^2 = a_4 li + b_4 lj + c_4 lk + d_4 l^2.$

But kl contains no term in l, so that $d_4 = 0$.
$kl = il^2 = a_4 j, \quad b_{34} = a_4, \quad c_{34} = 0,$
$0 = l^3 = b_{34} k + c_4 b_{34} j, \quad b_{34} = a_4 = 0 = kl, \quad l^2 = b_4 j + c_4 k,$
$kil = k^2 = b_{31} jl = 0, \quad 0 = kli = b_{31} ki = b_{31}^2 j = b_{31} = ki = lj,$
$li = b_{41} j + c_{41} k, \quad lk = lil = 0.$

There are two cases:

[231^1], when c_{41} does not vanish;
[2312], when c_{41} vanishes.

[231^1]. The defining formula of this case is

$$c_{41} \neq 0,$$

and if p is determined by the equation

$$c_{41} p^2 + (c_4 - b_{41}) p = b_4,$$

we have

$$i(l + pi) = k + pj,$$
$$(l + pi)^2 = (c_4 + pc_{41})(k + pj),$$

so that $l + pi$ and $k + pj$ may be substituted respectively for l and k, which is the same as to make

$$b_4 = 0,$$

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and there are two cases

$\left[\frac{1}{2}\right]$ when ϵ_1^2 has the $+$ value.
$\left[\frac{1}{2}\right]_i$ when ϵ_1^2 has the $-$ value.

[21.] The defining equation of this case may be written

$$\epsilon^2 = \epsilon.$$

This gives a quadruple algebra whose multiplication table may be written [illegible] the multiplication table being*

ϵ_1	i	j	k	l
i	j	0	0	k
j	0	0	0	0
k	0	0	0	0
l	k	0	0	k

[21.1.] The defining equation of this case is

$$\epsilon^2 = \epsilon.$$

---

* I, i. e. the one ϵ_1, or what has been written $\epsilon_1 = 1$. In all cases when new letters of the alphabet of the algebra are introduced, the multiplications remain with them. [illegible] $\epsilon_1 \epsilon = \epsilon$.

† When $\beta = 1$, $\epsilon \pm 1$, we have $(\epsilon - 1)^2 = (\epsilon - 1)$; so that in the substitution $\epsilon - 1$ for ϵ, the algebra is broken up into two of the form ϵ, $1 - \epsilon$. When $\beta = 1$, $\epsilon = 1$, in substituting $\epsilon = 1 - i$, $j = j - \epsilon k$, $\epsilon = \epsilon - l$, $l = \epsilon - l$, we have $\epsilon = \epsilon$; $\epsilon^2 = \epsilon$; $\epsilon \epsilon = \epsilon$; so that the algebra reduces to ϵ, $1 - \epsilon$. When $\beta = 1$, $\epsilon = 1$, in putting $\epsilon = \epsilon' + \epsilon''$, we have $\epsilon^2 = \epsilon$, $\epsilon'^2 = \epsilon'$, $\epsilon'' = \epsilon''$, so that the algebra reduces to ϵ', ϵ''. When $\beta = 1$, $\epsilon = 1$, in putting $\epsilon = \epsilon' + \epsilon'' - 1$, $j = j_1 + \epsilon - \epsilon'$, $k = \epsilon k$, we have $\epsilon^2 = \epsilon^2 = \epsilon$, $\epsilon = \epsilon$; so that the algebra reduces to ϵ, $1 - \epsilon$. When $\beta = -1$, $\epsilon \pm 1$, in putting $\epsilon = \epsilon' + \epsilon'' - 1$, $j = j_1 - \epsilon k + k$, $k = \epsilon k - k$, $l = \epsilon l - k$, we get the multiplication table of ϵ, $1 - \epsilon$. When $\beta = -1$, $\epsilon = 1$, in putting $\epsilon = \epsilon' + \epsilon'' - 1$, $j = j_1 - \epsilon k + k$, $k = \epsilon k - k$, $l = \epsilon l - k$, we get the following multiplication table, which may replace that in the text:

ϵ_1	i	j	k	l
i	j	0	0	j
j	0	0	0	0
k	0	0	0	0
l	k	0	0	0

In relative form, $i = A : B \rightarrow B : C \rightarrow A : D$, $j = A : C$, $k = A : E$, $\epsilon = A \mid B \rightarrow D : E$. [C. S. P.]

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There are two cases:

$[231^2 21]$, when $b_{\alpha\alpha}$ does not vanish;
$[231^2 2^2]$, when $b_{\alpha\alpha}$ vanishes.

$[231^2 21]$. The defining formula of this case is

$$b_{\alpha\alpha} \neq 0.$$

There are two cases:

$[231^2 21^2]$, when $c_{\alpha\alpha} + 1$ does not vanish;
$[231^2 212]$, when $c_{\alpha\alpha} + 1$ vanishes.

$[231^2 21^2]$. The defining formula of this case is

$$c_{\alpha\alpha} + 1 \neq 0$$

so that

$$l\frac{b_{\alpha\alpha} i + c_{\alpha\alpha} l}{c_{\alpha\alpha} + 1} = \frac{b_{\alpha\alpha}^2 j + b_{\alpha\alpha} c_{\alpha\alpha} k}{c_{\alpha\alpha} + 1},$$

$$\frac{b_{\alpha\alpha} i + c_{\alpha\alpha} l}{c_{\alpha\alpha} + 1} l = \frac{b_{\alpha\alpha} k}{c_{\alpha\alpha} + 1}, \quad \left(\frac{b_{\alpha\alpha} i + c_{\alpha\alpha} l}{c_{\alpha\alpha} + 1}\right)^3 = \frac{b_{\alpha\alpha} + c_{\alpha\alpha}}{c_{\alpha\alpha} + 1} \cdot \frac{b_{\alpha\alpha} j + c_{\alpha\alpha} k}{c_{\alpha\alpha} + 1}$$

so that the substitution of $\frac{b_{\alpha\alpha} i + c_{\alpha\alpha} l}{c_{\alpha\alpha} + 1}$, $\frac{b_{\alpha\alpha}^2 j + b_{\alpha\alpha} c_{\alpha\alpha} k}{c_{\alpha\alpha} + 1}$, and $\frac{b_{\alpha\alpha} k}{c_{\alpha\alpha} + 1}$, respectively, for i, j, and k, is the same as to assume

$$c_{\alpha\alpha} = 0, \quad b_{\alpha\alpha} = j,$$

which reduces this case to [2312].

$[231^2 212]$. The defining equation of this is easily reduced to

$$li = j - k.$$

This gives a quadruple algebra which may be called (m_4), its multiplication table being

(m_4)	i	j	k	l
i	j	0	0	k
j	0	0	0	0
k	0	0	0	0
l	$j-k$	0	0	0

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The substitution of $i - l$ and $j - k$, respectively, for i and j transforms this algebra into one of which the multiplication table is *

(m_4)	i	j	k	l
i	0	0	0	k
j	0	0	0	0
k	0	0	0	0
l	j	0	0	0

[231·2]. The defining equation of this case is

$$li = c_{41}k.$$

This gives a quadruple algebra which may be called (n_4), its multiplication table being †

(n_4)	i	j	k	l
i	j	0	0	k
j	0	0	0	0
k	0	0	0	0
l	ck	0	0	0

[2312]. The defining equation of this case is

$$li = b_{41}j,$$

which gives

$$(l - b_{41}i)\,i = 0,$$

so that the substitution of $l - b_{41}i$ for l passes this case virtually into [232].

* $i = A:B + C:D$. $j = B:D$. $k = A:C$. $l = B:C$. [C. S. P.]

† In relative form. $i = A:B + B:C + D:E$. $j = A:C$. $k = A:E$. $l = B:E + cA:D$. When $c = 0$ the algebra reduces to (q_4). [C. S. P.]

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[232]. The defining equation of this case is

$$il = 0,$$

and it may be assumed that

$$ki = 0,$$

$$0 = jl = kj = ik^2 = k^2i = ikl = ilk = lki = il^2$$

$$k^2 = b_3j + c_3k + d_3l, \quad li = b_{41}j + c_{41}k + d_{41}l,$$

$$lj = d_{41}li, \quad 0 = lji = d_{41}lj = d_{41}^2li = d_{41} = lj.$$

There are two cases:

[2321], when c_{41} does not vanish;
[232²], when c_{41} vanishes.

[2321]. The defining equation of this case is easily reduced to

$$li = k,$$

which gives

$$0 = lik = l^2 = lil = kl$$

$$lk = l^2i = a_4j + d_4k,$$

$$0 = l^3k = d_4l^2k = d_4^2lk = d_4, \quad lk = a_4j = l^2i,$$

$$l^2 = a_4i + b_4j + c_4k,$$

$$0 = l^3 = a_4k + c_4a_4j = a_4 = lk.$$

There are two cases:

[2321²], when c_4 does not vanish;
[23212], when c_4 vanishes.

[2321²]. The defining equation of this case can be reduced to

$$c_4 = 1$$

which gives a quadruple algebra which may be called (o_4), its multiplication table being *

(o_4)	i	j	k	l
i	j	0	0	0
j	0	0	0	0
k	0	0	0	0
l	k	0	0	$bj + k$

* In relative form, $i = A : E + E : D + B : C$, $j = A : D$, $k = A : C$, $l = A : B + B : C + bB : D$. When $b = 0$, this algebra reduces to (r_4). When $b = -1$, the substitution of $i - l$ for l reduces it to (l_4). [C. S. P.]

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[23212]. The defining equation of this case is

$$i^2 = b_4 j .$$

There are two cases:

[232121]. when b_4 does not vanish;
[232122]. when b_4 vanishes.

[232121]. The defining equation of this case can be reduced to

$$i^2 = j .$$

This gives a quadruple algebra which may be called (p_4). its multiplication table being*

(p_4)	i	j	k	l
i	j	0	0	0
j	0	0	0	0
k	0	0	0	0
l	k	0	0	j

[232122]. The defining equation of this case is

$$i^2 = 0 .$$

This gives a quadruple algebra which may be called (q_4). its multiplication table being†

(q_4)	i	j	k	l
i	j	0	0	0
j	0	0	0	0
k	0	0	0	0
l	k	0	0	0

* In relative form, $i = A:B+B:D+C:E$, $j = A:D$, $k = A:E$, $l = A:C+C:D$. [C. S. P.]
† In relative form, $i = A:C+C:D$, $j = A:D$, $k = B:D$, $l = B:C$. [C. S. P.]

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[232²]. The defining equation of this case is

$$li = b_{41}j$$

and we have

$$\begin{aligned} k^2 &= b_{24}j + c_2k + d_2l \\ kl &= b_{34}j + c_{34}k + d_{34}l \\ lk &= b_{43}j + c_{43}k + d_{43}l \\ l^2 &= b_{44}j + c_4k + d_4l \end{aligned}$$

so that there can be no pure algebra in this case if b_{41} vanishes,* and it may be assumed without loss of generality that

$$li = j.$$

There are two cases:

[232²1], when d_2 does not vanish;
[232²], when d_2 vanishes.

[232²1]. The defining equation of this case can be reduced to

$$k^2 = l,$$

which gives

$$0 = k^3 = kl = lk = k^2l = l^3,$$

and there is no pure algebra in this case.†

[232²]. The defining equation of this case is

$$d_2 = 0,$$

which gives

$$\begin{aligned} 0 = k^3 &= c_2k^2 = c_2, \quad k^2 = b_{24}j, \\ 0 = k^2l &= c_{34}k^2 + d_{34}kl = d_{34} = b_{24}c_{34}, \\ 0 = lk^2 &= c_{43}k^2 + d_{43}kl = d_{43} = b_{24}c_{43}. \end{aligned}$$

There are two cases:

[232²1], when b_{24} does not vanish;
[232⁴], when b_{24} vanishes.

[232²1]. The defining equation of this case can be reduced to

$$k^2 = j,$$

which gives

$$0 = c_{34} = c_{43}, \quad kl = b_{34}j, \quad lk = b_{43}j,$$
$$k(l - b_{34}j) = 0,$$

* In this case, j, k and l, might form any one of the algebras (b_4), (e_3), (d_3) or (e_3). [C. S. P.]
† The case is impossible because $ki = 0$ and $k^2i = j$. [C. S. P.]

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so that $l - h_{ij}j$ can be substituted for l without loss of generality, which is the same as to assume

$$l^2 = 1,$$

and this gives

$$0 = l^3 = jl^2 = jl = ej^2 = ej = l^2 = e,$$

so that there is no pure algebra in this case.*

[23D]. The defining equations of this case are

$$k^2 = 0,$$

which gives

$$0 = kj = jk = kl = lk,$$
$$0 = k^3 = e_{ik}k = e_{ik}. \quad k^2 = h_{ij}j.$$
$$0 = jk = e_{jk}k = e_{jk}. \quad k = l_{ij}j.$$

and there can be no pure algebra if e_{ij} vanishes, so that it may be assumed, without loss of generality, that

$$j = 1$$

which gives

$$0 = j = k = l^2.$$

This gives a quadruple algebra which may be called (e_{ij}), its multiplication table being†

(e_{ij})	i	j	k	l
i	j	0	0	0
j	0	0	0	0
k	0	0	0	0
l	j	0	0	k

[24]. The defining equations of this case are

$$i^2 = j^2 = k^2 = l^2 = 0.$$

* Substituting $i - l$ for i, this case is $i = B:D.\ j = A:D.\ k = A:C - C:D.\ l = A:B.$ [C. S. P.]

† $i = A:B + B:D - C:D.\ j = A:D.\ k = A:E.\ l = A:C - C:E.$ [C. S. P.]

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and it may be assumed, from §§ 63 and 65, that

$$ij = k = -ji, \quad il = li = 0,$$

which give

$$0 = ik = ki = jk = kj = kl = lk,$$
$$0 = ijl = b_{21}k = b_{21} = j^2l = -a_{21}k + d_{21}jl = d_{21} = a_{21},$$
$$jl = -lj = c_{21}k,$$

so that there is no pure algebra in this case.*

QUINTUPLE ALGEBRA.

There are two cases:

[1], when there is an idempotent basis;
[2], when the algebra is nilpotent.

[1]. The defining equation of this case is

$$i^3 = i.$$

There are eleven cases:

[1^3], when j, k, l and m are all in the first group;
[12], when j, k and l are in the first, and m in the second group;
[13], when j and k are in the first, and l and m in the second group;
[14], when j and k are in the first, l in the second, and m in the third group;
[15], when j is in the first, and k, l and m in the second group;
[16], when j is in the first, k and l in the second, and m in the third group;
[17], when j is in the first, k in the second, l in the third, and m in the fourth group;
[18], when j, k and l are in the second, and m in the third group;
[19], when j and k are in the second, and l and m in the third group;
[1^{0}], when j and k are in the second, l in the third, and m in the fourth group;
[11^{1}], when j is in the second, k in the third, and l and m in the fourth group.

[1^2]. The defining equations of this case are

$$ij = ji = j, \quad ik = ki = k, \quad il = li = l, \quad im = mi = m.$$

The algebras deduced by §69 from algebras (i_4) to (r_4) may be named (a_5) to (j_5), and their multiplication tables are respectively

*$i = -A:C + B:E$, $j = A:B + C:E + cD:E$, $k = A:E$, $l = -A:D + cB:E$. [C. S. P.]

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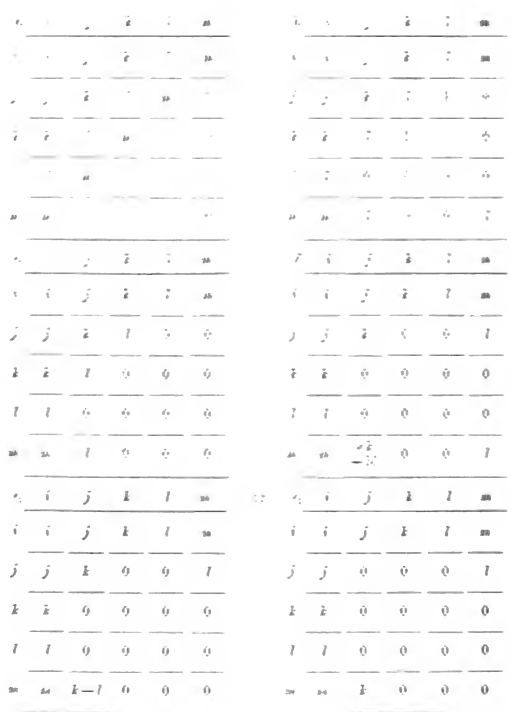

(f_5)

	i	j	k	l	m
i	i	j	k	l	m
j	j	k	0	0	l
k	k	0	0	0	0
l	l	0	0	0	0
m	m	al	0	0	0

(g_5)

	i	j	k	l	m
i	i	j	k	l	m
j	j	k	0	0	0
k	k	0	0	0	0
l	l	0	0	0	0
m	n	l	0	0	$l+ak$

(h_5)

	i	j	k	l	m
i	i	j	k	l	m
j	j	k	0	0	0
k	k	0	0	0	0
l	l	0	0	0	0
m	m	l	0	0	k

(i_5)

	i	j	k	l'	m
i	i	j	k	l	m
j	j	k	0	0	0
k	k	0	0	0	0
l	l	0	0	0	0
m	m	l	0	0	0

(j_5)

	i	j	k	l	m
i	i	j	k	l	m
j	j	k	0	0	0
k	k	0	0	0	0
l	l	0	0	0	0
m	m	k	0	0	l

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[12]. The defining equations of this case are

$$ij = ji = j, \quad ik = ki = k, \quad il = li = l, \quad im = m, \quad mi = 0,$$

which give, by § 46,

$$0 = mj = mk = ml = m^2,$$

and if A is any expression belonging to the first group, but not involving i, we have the form

$$Am = am,$$

and by § 67, A is nilpotent, so that there is some power n which gives

$$0 = A^n = A^n m = aA^{n-1}m = a^n m = a = Am,$$
$$0 = jm = km = lm;$$

and there is no pure algebra in this case.*

[13]. The defining equations of this case are

$$ij = ji = j, \quad ik = ki = k, \quad il = l, \quad im = m, \quad li = mi = 0,$$

which give, by § 46,

$$0 = lj = lk = l^2 = lm = mj = mk = ml = m^2;$$

and it may be assumed from (a_3), by § 69, that

$$j^2 = k, \quad j^3 = 0.$$

It may also be assumed that

$$jl = m, \quad \text{whence}\dagger \quad kl = jm = 0.$$

We thus obtain a quintuple algebra which may be called (k_5), its multiplication table being this: ‡

---

* In fact i and m, by themselves, form the algebra (b_2), while i, j, k, l, by themselves form one of the algebras (a_4), (b_4), (c_4), (d_4), the products of m with j, k and l vanishing. [C. S. P.]

† This is proved as follows: $0 = j^2 l = j^3 m = d_1 jl + e_1 jm = d_1 e_{11} l + (d_{12} + e_{12}^2)m$. Thus $d_{11}e_{12} = 0$ and $d_{11} + e_{12}^2 = 0$; or $d_{12} = 0$, $e_{11} = 0$, $jm = kl = 0$. [C. S. P.]

‡ $i = A : A + B : B + C : C$, $j = A : B + B : C$, $k = A : C$, $l = B : D$, $m = A : D$. [C. S. P.]

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(k_3)	i	j	k	l	m
i	i	j	k	l	m
j	j	k	0	m	0
k	k	0	0	0	0
l	0	0	0	0	0
m	0	0	0	0	0

[14]. The defining equations of this case are

$$ij = ji = j, \quad ik = ki = k, \quad il = l, \quad mi = m, \quad li = im = 0,$$

which give, by § 46,

$$0 = jm = km = lj = lk = l^2 = ml = m^2.$$

It may be assumed from § 69 and (a_3) that

$$j^2 = k, \quad j^2 = 0,$$

whence

$$0 = jl = kl = mj = mk = jlm = a_{45}j + b_{45}k = a_{45} = b_{45}. \quad lm = c_{45}k,$$

and there is no pure algebra in this case.*

[15]. The defining equations of this case are

$$ij = ji = j, \quad ik = k, \quad il = l, \quad im = m, \quad ki = li = mi = 0,$$

which give, by §§ 46 and 67,

$$0 = j^2 = kj = k^2 = kl = km = lj = lk = l^2 = lm = mj = mk = ml = m^2.$$

It may be assumed that $jk = l, \cdot jm = 0$,†

whence, $jl = 0$,

and there is no pure algebra in this case.‡

---

* $i = A : A + B : B + C : C$, $j = A : B + B : C$, $k = A : C$, $l = A : D$, $m = cD : C$. [C. S. P.]

† We cannot suppose $jk = k$, because $j^2k = 0$. We may, therefore, put l for jk. Then $jl = 0$. Then, $0 = j^2m = e_{33}e_{33}k + (d_{33}e_{33} + e_{33}d_{33})\,l + e_{33}^2m$. It follows that $jm = d_{33}l$, and substituting $m - d_{33}k$ for m, we have $jm = 0$. The algebra thus separates into (b_3) and (e_4). [C. S. P.]

‡ $i = A : A + B : B$, $j = A : B$, $k = B : C$, $l = A : C$, $m = A : D$. [C. S. P.]

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[10]. The defining equations of this case are

$$ij = ji = j. \quad ik = k. \quad i^2 = i. \quad mi = m. \quad ki = i = im = 0.$$

which give, by §§ 45 and 47,

$$0 = j^2 = jm = kj = k^2 = l^2 = lj = lk = l^2 = mj = mk = m^2 = m^3.$$
$$km = a_{31}i + b_{31}j. \quad lm = a_{41}i + b_{41}j.$$

and it may be assumed that

$$jk = d_{23}l. \quad jl = 0.$$

and d_{23} cannot vanish in the case of a pure algebra,* so that it is no loss of generality to assume

$$jk = l.$$

which gives

$$jkm = lm = a_{31}j.$$

There are two cases:

[101]. when a_{31} does not vanish:
[102]. when a_{31} vanishes.

[101]. The defining equation of this case can be reduced to

$$a_{31} = 1.$$

which gives $\quad lm = j. \quad km = i + b_{31}j.$

and $i + b_{31}j$ can be substituted for i, and this gives a quintuple algebra which may be called (l_1), of which the multiplication table is

(l_1)	i	j	k	l	m
i	i	j	k	l	0
j	i	0	l	0	0
k	0	0	0	0	i
l	0	0	0	0	j
m	m	0	0	0	0

* But $0 = mk = km = k^2 = a_{11}i + b_{11}j$. $k = a_{11}k + d_{11}b_{11}l$. Hence $a_{11} = 0$ and either d_{11} or $b_{11} = 0$, and in either case there is no pure algebra. The two algebras l_1 and m_1 are incorrect, as may be seen by comparing $k \cdot mk$ with $km \cdot k$. [C. S. P.]

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[162]. The defining equation of this case is

$$a_{25} = 0,$$

which gives

$$km = b_{25}j, \quad lm = 0;$$

and b_{25} cannot vanish in the case of a pure algebra, so that it is no loss of generality to assume

$$km = j.$$

This gives a quintuple algebra which may be called (m_5), of which the multiplication table is

(m_5)	i	j	k	l	m
i	i	j	k	l	0
j	j	0	l	0	0
k	0	0	0	0	j
l	0	0	0	0	0
m	m	0	0	0	0

[17]. The defining equations of this case are

$$ij = ji = j, \quad ik = k, \quad li = l, \quad ki = il = im = mi = 0,$$

which give, by §§ 46 and 67,

$$0 = j^2 = jk = jl = jm = kj = k^2 = lj = l^2 = lm = mj = mk,$$
$$kl = a_{24}i + b_{24}j, \quad km = c_{25}k, \quad lk = c_{43}m, \quad ml = d_{54}l, \quad m^2 = e_5 m,$$
$$0 = jkl = a_{24}j = a_{24},$$
$$lkl = b_{24}lj = 0 = c_{43}ml = c_{43}d_{54}, \quad klk = b_{24}jk = 0 = c_{25}km = c_{43}c_{25},$$
$$lkm = c_{25}lk = c_{25}m^2 = c_{25}c_{43}m = 0 = c_{25}e_5,$$
$$kml = d_{54}kl = c_{25}kl, \quad (d_{54} - c_{25})\, b_{24} = 0, \quad km^2 = e_5 km = c_{25}km, \quad (e_5 - c_{25})\, c_{25} = 0,$$
$$m^2 l = e_5 ml = d_{54}ml, \quad (e_5 - d_{54})\, d_{54} = 0.$$

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There are two cases:

[171]. when $c_1 = 1$.*

[172]. when $c_1 = 0$.

[171]. The defining equation of this case is

$$m^2 = m.$$

which gives

$$0 = c_m = c_k.$$

There can be no pure algebra if either of the quantities b_m, c_m or d_m vanish, and there is no loss of generality in assuming

$$kl = j, \quad km = k, \quad ml = l.$$

This gives a quintuple algebra which may be called (a_5), its multiplication table being

(a_5)	i	j	k	l	m
i	i	j	k	0	0
j	j	0	0	0	0
k	0	0	0	j	k
l	l	0	0	0	0
m	0	0	0	l	m

[172]. The defining equation of this case is

$$m^2 = 0.$$

which gives

$$0 = c_m = d_m = km = ml;$$

* But on examination of the assumptions already made, it will be seen that if c_1 is not zero, and consequently $c_{11} = 0$, the algebra breaks up into two. Accordingly, the algebra a_1 is impure, for i, j, k and l, alone, form the algebra f_4, while m, l, k, j, alone, form the algebra h_4, and $im = mi = 0$. [C. S. P.]

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and there can be no pure algebra if either b_{34} or c_{43} vanishes, and it may be assumed that

$$kl = j, \quad lk = m.$$

This gives a quintuple algebra which may be called (o_5), its multiplication table being as follows:*

(o_5)	i	j	k	l	m
i	i	j	k	0	0
j	j	0	0	0	0
k	0	0	0	j	0
l	l	0	m	0	0
m	0	0	0	0	0

[18]. The defining equations of this case are

$$ij = j, \quad ik = k, \quad il = l, \quad mi = m, \quad ji = ki = li = im = 0,$$

which give, by § 46,

$$0 = j^3 = jk = jl = kj = k^3 = kl = lj = lk = l^3 = mj = mk = ml = m^3.$$

But if A is any expression of the second group,

$$Am = ai;$$

which gives

$$0 = Amj = aj = a = Am = jm = km = lm,$$

and there is no pure algebra in this case.

[19]. The defining equations of this case are

$$ij = j, \quad ik = k, \quad li = l, \quad mi = m, \quad il = im = ji = ki = 0,$$

which give, by § 46,

$$0 = j^3 = jk = kj = k^3 = lj = lk = l^3 = lm = mj = mk = ml = m^3.$$

* $i = R : B + D : D + F : F$, $j = D : F$, $k = B : C + D : E$, $l = A : B + E : F$, $m = A : C$. [C. S. P.]

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But if A is an expression of the second group and B one of the third,

$$AB = ai.$$

which gives

$$0 = ABj = aj = a = AB = j^2 = jm = kl = lm,$$

and there is no pure algebra in this case.

[10'5]. The defining equations of this case are

$$ij = j, \quad ik = k, \quad li = l, \quad ji = ki = il = im = mi = 0,$$

which give, by § 45,

$$0 = j^2 = jk = kj = k^2 = l^2 = lm = mj = mk;$$

and it is obvious that we may assume

$$jl = 0.$$

We have, then,

$$\begin{gathered} jm = b_{55}j + c_{55}k, \quad kl = a_{54}i, \quad km = b_{55}j + c_{55}k, \\ lj = e_{45}m, \quad lk = e_{45}m, \quad ml = d_{54}l, \quad m^2 = e_5 m, \\ 0 = d_{54}jl = jml = e_{55}kl = a_{54}e_{55}i = a_{54}e_{55}. \end{gathered}$$

There are two cases:

[10'51], when a_{54} does not vanish;
[10'52], when a_{54} vanishes.

[10'51]. The defining equation of this case can be reduced to

$$kl = i,$$

which gives

$$e_{55} = 0, \quad jm = b_{55}j.$$

There are two cases:

[10'51'], when $e_5 = 1$;
[10'512], when e_5 vanishes.

[10'51']. The defining equation of this case is

$$m^2 = m;$$

and we assume

$$jm = j, \quad ml = l, \quad km = k,$$

because otherwise this case would coincide with a subsequent one. We get, then,

$$0 = jlj = e_{45}jm = e_{45} = lj, \qquad 0 = jlk = e_{45}jm = e_{45} = lk,$$

which virtually brings this case under [10'52].*

* This does not seem clear. But $i = i^2 = klkl = 0$, which is absurd. [C. S. P.]

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[10·12]. The defining equation of this case is

$$m^3 = 0,$$

which gives

$$0 = jm^2 = b_{35}jm = b_{35} = jm, \quad 0 = m^2l = d_{53}ml = a_{54} = ml,$$
$$0 = km^2 = c_{35}km = c_{35}, \quad km = b_{35}j, \quad lkl = li = l = c_{43}ml = 0,$$

which is impossible, and this case disappears.

[10·2]. The defining equation of this case is

$$kl = 0.*$$

There are two cases:

[10·21], when $e_5 = 1$;
[10·22], when e_5 vanishes.

[10·21]. The defining equation of this case is

$$m^2 = m,$$

and if we would not virtually proceed to a subsequent case, we must assume

$$jm = j, \quad km = k, \quad ml = l,$$

and there is no loss of generality in assuming

$$lj = 0,$$

so that there is no pure algebra in this case.†

[10·22]. The defining equation of this case is

$$m^2 = 0,$$

which gives

$$0 = m^2l = d_{54}ml = d_{54} = ml;$$

and we may assume

$$c_{35} = 0,$$

which gives

$$0 = jm^2 = b_{35}jm = b_{35} = jm, \quad 0 = km^2 = c_{35}km = c_{35}, \quad km = b_{35}j,$$
$$0 = c_{43}m^2 = lkm \quad = b_{35}c_{43}m = b_{35}c_{43};\ddagger$$

* In this case, the algebra at once separates into an algebra between j, k, l and m, and three double algebras between i and j, i and k, and i and l, respectively. [C. S. P.]

† In fact, $0 = lklk = e_5^2 m = e_{11} = lk$. So that the algebra falls into six parts of the form (b_{11}). [C. S. P.]

‡ The author omits to notice that $0 = klk = e_{11}km = e_{11}b_{11}$. Thus, either $km = 0$ or $lj = lk = 0$. The algebra (p_{11}) involves an inconsistency in regard to klk. [C. S. P.]

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which give
$$0 = m^3 = jm^3 = b_{15}jm = b_{25} = jm\,,$$
$$0 = m^3k = c_{53}mk = c_{23} = mk\,;$$

and α_{23} cannot vanish in a pure algebra, so that we may assume
$$jk = i\,,$$
which gives
$$kjk = k = d_{22}c_{23}k\,,\quad kkj = j = d_{22}b_{24}j\,,\quad 1 = d_{22}c_{43} = d_{22}b_{24}\,,$$
$$jl = j^2 = b_{24}jl\,,\quad b_{24}^2 = b_{24} = 1\,,\quad lk = l^2k = c_{43}k\,,\quad c_{43}^2 = c_{43} = 1 = d_{22}\,,$$
$$jl = j\,,\quad lk = k\,,\quad kjl = l = kj\,,$$
and there is no pure algebra in this case.*

[11′12]. The defining equations of this case are
$$lm = ml = 0\,,$$
which give
$$0 = jlm = b_{24}jm = b_{24}b_{25}j = b_{24}b_{45}\,,\quad 0 = lmk = c_{53}lk = c_{43}c_{23}k = c_{43}c_{53}\,,$$
$$kjl = d_{22}l = b_{24}kj = b_{24}d_{22}l + b_{24}c_{23}m\,,\quad lkj = d_{22}l = c_{43}kj = c_{43}d_{22}l + c_{43}c_{23}m\,,$$
$$kjm = c_{53}m^2 = b_{24}kj = b_{24}d_{22}l + b_{24}c_{23}m\,,\quad mkj = c_{53}m^2 = c_{53}kj = c_{53}d_{22}l + c_{53}c_{23}m\,,$$
$$d_{22} = b_{24}d_{24} = c_{43}d_{24}\,,\quad 0 = b_{24}d_{24} = c_{53}d_{24} = b_{24}c_{24} = c_{43}c_{23}\,.\dagger$$

There are two cases:

[11′121], when m is idempotent;

[11′12²], when m is nilpotent.

[11′121]. The defining equation of this case is
$$m^2 = m\,,$$
which gives
$$c_{23} = c_{43}c_{23} = b_{24}c_{23}\,;$$
and it may be assumed that
$$b_{24} = 0\,.$$

But if the algebra is then regarded as having l for its idempotent basis, it is evident from § 50 that the bonds required for a pure algebra are wanting, so that there is no pure algebra in this case.‡

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* In fact, i, j, k, l form the algebra (g_4). and l, m, the algebra (b_2). [C. S. P.]

† The last equation holds by § 68. [C. S. P.]

‡ Namely, $d_{12} = 0$, and either $c_{32} = 1$, when l forms the algebra (a_1), and i, j, k, m the algebra (g_4), or else $c_{32} = 0$, when by [13] of triple algebra $\alpha_{12} = 0$, and j and k each forms the algebra (b_1) with each of the letters i, l, m. [C. S. P.]

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[11'12²]. The defining equation of this case is

$$m^3 = 0,$$

which gives

$$0 = jm^3 = b_{2,2}jm = b_{2,2}^2 j = b_{2,2} = jm, \quad 0 = m^3k = c_{3,3}mk = c_{3,3}^2 k = c_{3,3} = mk,$$
$$1 = b_{2,1} = c_{3,2}. \quad jl = j, \quad lk = k, \quad 0 = c_{3,1},$$

and there is no pure algebra in this case.*

[11'2]. The defining equation of this case is

$$l^n = 0,$$

in which n is 2 or 3. We must then have

$$0 = lm = ml = m^2,$$

which give

$$0 = jl^3 = b_{1,1}jl^3 = b_{1,1}^3 jl = b_{2,1} = jl = jm = lk = mk, \quad 0 = kjk = a_{2,2}k = a_{2,1} = jk,$$

and there is no pure algebra in this case.†

[2]. The defining equation of this case is

$$i^n = 0.$$

There are five cases:

[21], when $n = 6$;
[2²], when $n = 5$;
[23], when $n = 4$;
[24], when $n = 3$;
[25], when $n = 2$.

[21]. The defining equation of this case is

$$i^5 = 0,$$

and by § 60,

$$i^5 = j, \quad i^7 = k, \quad i^4 = l, \quad i^8 = m.$$

This gives a quintuple algebra which may be called (q_5), its multiplication table being

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* Here, m forms the algebra (b_1), and the other letters form (g_4). [C. S. P.]

† Namely, if $n = 2$, j, l, k, form the algebra (d_4) (second form), i, j, and i, k, the algebra (b_2), and m the algebra (c_1). But if $n = 3$, j, k, l and m form an algebra transformable into (j_4) or (k_4), while i, j, and i, k form, each pair, the algebra (b_2). [C. S. P.]

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(q_5)	i	j	k	l	m
i	j	k	l	m	0
j	k	l	m	0	0
k	l	m	0	0	0
l	m	0	0	0	0
m	0	0	0	0	0

[2⁸]. The defining equation of this case is

$$i^5 = 0,$$

and by § 59,

$$i^2 = j, \quad i^3 = k, \quad i^4 = l.$$

There are then by § 64 two quintuple algebras which may be called (r_5) and (s_5), their multiplication tables being

(r_5)	i	j	k	l	m
i	j	k	l	0	0
j	k	l	0	0	0
k	l	0	0	0	0
l	0	0	0	0	0
m	l	0	0	0	l

(s_5)	i	j	k	l	m
i	j	k	l	0	0
j	k	l	0	0	0
k	l	0	0	0	0
l	0	0	0	0	0
m	l	0	0	0	0

[23]. The defining equation of this case is

$$i^4 = 0;$$

and by § 59,

$$i^2 = j, \quad i^3 = k;$$

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and it may be assumed, from the principle of § 63, that

$$il = 0,$$

which gives

$$0 = jl = kl = li = il^2 = ilm$$
$$li = c_{41}k + d_{41}l + e_{41}m, \quad l^2 = c_4k + d_4l + e_4m, \quad lm = c_{45}k + d_{45}l + e_{45}m.$$

There are two cases:

[231], when $im = l$;
[232], when $im = 0$.

[231]. The defining equation of this case is

$$im = l,$$

whence

$$0 = jm = km = jmi = jml = jm^2 = e_{43} = e_4 = e_{45},$$
$$li^2 = d_4li, \quad 0 = li^3 = d_{41}li^2 = d_{41}^2li^2 = d_{41}^3li = d_{41} = lj = lk,$$
$$l^2 = d_4l^2, \quad 0 = l^3 = d_4l^2 = d_4, \quad li = c_{43}k, \quad l^2 = c_4k, \quad lm = c_{45}k + d_{45}l,$$
$$imi = li = c_{41}k, \quad mi = c_{41}j + c_{51}k + d_{51}l, \quad mj = c_{41}(1 + d_{51})k, \quad mk = 0,$$
$$iml = l^2 = c_4k, \quad ml = c_4j + c_5k + d_5l,$$
$$im^2 = lm = c_{45}k + d_{45}l, \quad m^2 = c_{45}j + c_5k + d_5l + d_{45}m,$$
$$0 = m^4 = d_{45}, \quad lim = l^2 = c_{41}km = 0 = iml = d_5c_{41}k = d_{54}c_{41},$$
$$0 = iml m = d_{54}lm = d_{54}c_{45}, \quad 0 = m^3l = d_{54}ml = d_{54}^2.*$$

There are two cases:

[231¹], when c_{41} does not vanish;
[2312], when c_{41} vanishes.

[231¹]. The defining equation of this case is reducible to

$$li = k.$$

There are two cases:

[231$^{1}_{2}$], when c_{45} does not vanish;
[231$^{1}_{2}$2], when c_{45} vanishes.

[231$^{1}_{2}$]. The defining equation of this case can be reduced to

$$lm = k,$$

which gives

$$m^2i = k + d_{51}k + d_{51}^2k = k + d_5k, \quad d_5 = d_{51} + d_{51}^2,$$
$$m^2 = k + d_{51}k + d_5d_{51}k = d_5k, \quad d_{51}^2 = -1;$$

* To these equations are to be added the following, which is taken for granted below: $ml = mim = e_{45}d_{51}k$. [C. S. P.]

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and if $\mathfrak{r}$ is one of the imaginary cube roots of -1, there are two cases:

$$[231^{1}],\quad \text{when } d_{31}=\mathfrak{r};$$
$$[231^{2}],\quad \text{when } d_{31}=-1.$$

[231^{1}]. The defining equation of this case is

$$d_{31}=\mathfrak{r},$$

which gives

$$\begin{aligned}
&i(m-c_{31}l)=l,\quad l(m-c_{31}l)=k,\\
&(m-c_{31}l)i=j+\mathfrak{r}l,\quad (m-c_{31}l)j=(1+\mathfrak{r})k,\\
&(m-c_{31}l)k=0,\quad (m-c_{31}l)l=\mathfrak{r}k,\\
&(m-c_{31}l)^{3}=j+[c_{5}-c_{31}(1+\mathfrak{r})]k+(2\mathfrak{r}-1)l;
\end{aligned}$$

so that the substitution of $m-c_{31}l$ for m is the same as to make

$$c_{31}=0.$$

There are two cases:

$$[231^{1}],\quad \text{when } c_{5} \text{ does not vanish};$$
$$[231^{2}],\quad \text{when } c_{5} \text{ vanishes}.$$

[231^{1}]. The defining equation of this case can be reduced to

$$c_{5}=1.$$

There is then a quintuple algebra which may be called (t_{5}), its multiplication table being *

* The author has overlooked the circumstance that (t_{5}) and (u_{5}) are forms of the same algebra. If in (t_{5}) we put $i_{1}=i-\mathfrak{r}^{2}j$, $j_{1}=j-3\mathfrak{r}^{2}k$, $k_{1}=k$, $l_{1}=-\mathfrak{r}^{2}k+l$, $m_{1}=-\mathfrak{r}^{2}j+m$, we get (u_{5}). The structure of this algebra may be shown by putting $i_{1}=\mathfrak{r}i$, $j_{1}=\mathfrak{r}^{2}j$, $k_{1}=-k$, $l_{1}=\mathfrak{r}^{2}j-\mathfrak{r}l$, $m_{1}=\mathfrak{r}i-m$, when we have this multiplication table [where the subscripts are dropped]:

(u_{5})	i	j	k	l	m
i	j	k	0	k	l
j	k	0	0	0	k
k	0	0	0	0	0
l	$\mathfrak{r}k$	0	0	0	0
m	$\mathfrak{r}l$	$\mathfrak{r}^{2}k$	0	0	0

In relative form, $i=A:B+A:C+B:E+C:D+E:G$, $j=A:D+A:E+B:G$, $k=A:G$, $l=\mathfrak{r}A:E+C:G$, $m=\mathfrak{r}^{2}A:B+A:F+\mathfrak{r}C:E+D:G-F:G$. [C. S. P.]

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(t_5)	i	j	k	l	m
i	j	k	0	0	l
j	k	0	0	0	0
k	0	0	0	0	0
l	k	0	0	0	k
m	$j+\mathfrak{r}l$	$(1+\mathfrak{r})k$	0	$\mathfrak{r}k$	$j+k+(2\mathfrak{r}-1)l$

[231^{1}2]. The defining equation of this case is

$$c_5 = 0 .$$

There is then a quintuple algebra which may be called (u_5), its multiplication table being

(u_5)	i	j	k	l	m
i	j	k	0	0	l
j	k	0	0	0	0
k	0	0	0	0	0
l	k	0	0	0	k
m	$j+\mathfrak{r}l$	$(1+\mathfrak{r})k$	0	$\mathfrak{r}k$	$j+(2\mathfrak{r}-1)l$

[231^{3}2]. The defining equation of this case is

$$d_{51} = -1 ,$$

which gives

$$d_5 = 0 , \quad i(m - c_{51}l) = l , \quad l(m - c_{51}l) = k ,$$
$$(m - c_{51}l)i = j - l , \quad (m - c_{51}l)l = -k , \quad (m - c_{51}l)_3 = j + c_5 k ;$$

so that the substitution of $m - c_{51}l$ * for m is the same as to make

$$c_{51} = 0 .$$

* The original text has $m - c_{5,1}k$ throughout these equations, but it is plain that $m - c_{5,1}l$ is meant. [C. S. P.]

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There are two cases:

[231³21], when c_3 does not vanish;

[231³2²], when c_3 vanishes.

[231³21]. The defining equation of this case can be reduced to

$$c_3 = 1.$$

There is a quintuple algebra which may be called (v_3), its multiplication table being*

(v_3)	i	j	k	l	m
i	j	k	0	0	l
j	k	0	0	0	0
k	0	0	0	0	0
l	k	0	0	0	k
m	$j-l$	0	0	$-k$	$j+k$

[231³2²]. The defining equation of this case is

$$c_3 = 0.$$

This gives a quintuple algebra which may be called (w_3), its multiplication table being*

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* The algebra (v_3) reduces to (w_3) on substituting $i_1 = i + \frac{1}{3}j + \frac{1}{3}l$, $j_1 = j + k$, $k_1 = k$, $l_1 = \frac{5}{3}k + l$, $m_1 = \frac{1}{3}j + \frac{1}{3}l + m$. To exhibit the structure of this algebra, we may put ρ and ρ' for imaginary cube roots of 1, and substitute in (w_3) $i_1 = i + \rho' m$, $j_1 = (1-\rho)j + k + \sqrt{-3}l$, $k_1 = 3k$, $l_1 = (1-\rho')j + k - \sqrt{-3}l$, $m_1 = i + \rho m$. Then, dropping the subscripts, we have this multiplication table.

	i	j	k	l	m
i	0	0	0	k	j
j	k	0	0	0	0
k	0	0	0	0	0
l	0	0	0	0	k
m	l	k	0	0	0

In relative form. $i = \rho' A : B + \rho C : F + \Im\rho D : E$, $j = \Im\rho A : C + \Im\rho' D : F$, $k = \Im A : D$, $l = \Im\rho' A : E + \Im\rho B : F$, $m = \rho A : D + \Im\rho' B : C + \rho E : F$. [C. S. P.]

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(w_3)	i	j	k	l	m
i	j	k	0	0	l
j	k	0	0	0	0
k	0	0	0	0	0
l	k	0	0	0	k
m	$j-l$	0	0	$-k$	$j+k$

[231²2]. The defining equation of this case is

$$lm = 0,$$

which gives

$$ml = 0, \quad m^2 = c_3 k + d_3 l, \quad m^2 i = d_3 k = [1 + d_{31}) k, \quad d_3 = 1 + d_{31},$$

and c_{31} may be made to vanish without loss of generality.

There are three cases:

[231²21], when neither d_{31} nor $d_{31} + 1$ vanishes;
[231²2²], when $d_{31} + 1$ vanishes;
[231²23], when d_{31} vanishes.

[231²21]. The defining formulae of this case are

$$d_{31} \neq 0, \quad d_{31} \neq -1.$$

There are two cases:

[231²21²], when c_3 does not vanish;
[231²212], when c_3 vanishes.

[231²21²]. The defining equation of this case can always be reduced to

$$c_3 = 1.$$

This gives a quintuple algebra which may be called (x_5), its multiplication table being*

* In relative form, $i = A:B + A:E + B:D + D:F$, $j = A:D + B:F$. $k = A:F$, $l = A:D$. $m = (1 + a)\,A:B + A:C + A:E + B:D + C:D + D:F + E:F$. [C. S. P.]

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(x_5)	i	j	k	l	m
i	j	k	0	0	l
j	k	0	0	0	0
k	0	0	0	0	0
l	k	0	0	0	0
m	$j+al$	$(1+a)k$	0	0	$k+(1+a)l$

[231^2212]. The defining equation of this case is

$$c_5 = 0 .$$

This gives a quintuple algebra which may be called (y_5), its multiplication table being *

(y_5)	i	j	k	l	m
i	j	k	0	0	l
j	k	0	0	0	0
k	0	0	0	0	0
l	k	0	0	0	0
m	$j+al$	$(1+a)k$	0	0	$(1+a)l$

[231^223]. The defining equation of this case is

$$d_{31} = -1 ,$$

which gives

$$mi = j - l, \quad mj = 0, \quad m^2 = c_5 k .$$

There are two cases:

[231^2211], when c_5 does not vanish;
[231^2203], when c_5 vanishes.

* The relative form is the same as that of (x_1): omitting from m the terms $A:E$ and $E:F$. [C. S. P.]

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[$231^2 2^1 1$]. The defining equation of this case can be reduced to

$$m^3 = k.$$

This gives a quintuple algebra which may be called (z_5), its multiplication table being*

(z_5)	i	j	k	l	m
i	j	k	0	0	l
j	k	0	0	0	0
k	0	0	0	0	0
l	k	0	0	0	0
m	$j-l$	0	0	0	k

[$231^2 2^2$]. The defining equation of this case is

$$m^3 = 0.$$

This gives a quintuple algebra which may be called (aa_5), its multiplication table being†

(aa_5)	i	j	k	l	m
i	j	k	0	0	l
j	k	0	0	0	0
k	0	0	0	0	0
l	k	0	0	0	0
m	$j-l$	0	0	0	0

*In relative form, $i = A:B+B:C+C:D$. $j = A:C+B:D$. $k = A:D$. $l = A:C$. $m = B:C + A:E+E:D$. [C. S. P.]

†In relative form, the same as (z_5), except that $m = B:C$. [C. S. P.]

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[231²23]. The defining equation of this case is

$$mi = j,$$

which gives

$$0 = (l - j)i = (m - i)i;$$

so that, by the substitution of $l - j$ for l and $m - i$ for m, this case would virtually be reduced to [232].

[2312]. The defining equation of this case is

$$li = 0,$$

which gives

$$mj = 0, \quad mim = ml = d_{31}lm, \quad d_{45} = 0, \quad c_{54} = d_{31}c_{45},$$
$$m^2i = d_{31}ml = c_{45}k, \quad c_{45} = d_{31}c_{54}, \quad m^3 = d_3lm = d_3ml, \quad d_3(c_{54} - c_{45}) = 0.$$

There are two cases:

[23121], when d_3 does not vanish;
[2312²], when d_3 vanishes.

[23121]. The defining equation of this case can be reduced to

$$d_3 = 1,$$

which gives

$$c_{45} = c_{54};$$

and it may be assumed without loss of generality that

$$c_3 = 0.*$$

There are two cases:

[23121²], when c_{45} does not vanish;
[231212], when c_{45} vanishes.

[23121²]. The defining equation of this case can be reduced to

$$lm = ml = k,$$

which gives

$$d_{31} = 1.$$

There are two cases:

[23121²], when c_{31} does not vanish;
[23121²2], when c_{31} vanishes.

[23121³]. The defining equation of this case can be reduced to

$$c_{31} = 1.$$

* Namely, by putting $l_1 = c_{31}k + l$, $m_1 = m - c_{31}j$. [C. S. P.]

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This gives a quintuple algebra which may be called (ab_5), its multiplication table being *

(ab_5)	i	j	k	l	m
i	j	k	0	0	l
j	k	0	0	0	0
k	0	0	0	0	0
l	0	0	0	0	k
m	$k+l$	0	0	k	$j+l$

[23121²2]. The defining equation of this case is

$$c_{51} = 0.$$

This gives a quintuple algebra which may be called (ac_5), its multiplication table being †

---

* The structure of this algebra is best seen on making the following substitutions: Let $\mathfrak{h}_1$ and $\mathfrak{h}_2$ represent the two roots of the equation $x^2 = x+1$. That is, $\mathfrak{h}_1 = \frac{1}{2}(1+\sqrt{5})$ and $\mathfrak{h}_2 = \frac{1}{2}(1-\sqrt{5})$. Then substitute $i_1 = \mathfrak{h}_1^{-1}(i+\mathfrak{h}_1 m)$, $j_1 = \mathfrak{h}_1^{-\frac{1}{2}}\{(2+\mathfrak{h}_1)j+\mathfrak{h}_1 k+(1+3\mathfrak{h}_1)l\}$, $k_1 = \frac{1}{5}k$, $l_1 = \mathfrak{h}_1^{-\frac{1}{2}}\{(2+\mathfrak{h}_2)j + \mathfrak{h}_2 k + (1+3\mathfrak{h}_2)l\}$, $m_1 = \mathfrak{h}_1^{-\frac{1}{2}}(i+\mathfrak{h}_2 m)$. Then, we have the multiplication table:

	i	j	k	l	m
i	j	k	0	0	$\frac{1}{5}\mathfrak{h}_1 k$
j	k	0	0	0	0
k	0	0	0	0	0
l	0	0	0	0	k
m	$\frac{1}{5}\mathfrak{h}_1 k$	0	0	k	l

In relative form, $i = A:B+B:C+C:D+\frac{1}{5}\mathfrak{h}_1 A:G+H:D$, $j = A:C+B:D$. $k = A:D$. $l = A:F + E:D$. $m = A:E+E:F+F:D+\frac{1}{5}\mathfrak{h}_1 A:H+G:D$. [C. S. P.]

† On making the same substitutions for i and m as in the last note, this algebra falls apart into two algebras of the form (b_2). [C. S. P.]

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(ac_5)	i	j	k	l	m
i	j	k	0	0	l
j	k	0	0	0	0
k	0	0	0	0	0
l	0	0	0	0	k
m	l	0	0	k	$j+l$

[231212]. The defining equation of this case is

$$ml = lm = 0.$$

There are two cases:

[2312121], when c_{51} does not vanish;
[231212*], when c_{51} vanishes.

[2312121]. The defining equation of this case can be reduced to

$$c_{51} = 1.$$

This gives a quintuple algebra which may be called (ad_5), its multiplication table being *

(ad_5)	i	j	k	l	m
i	j	k	0	0	l
j	k	0	0	0	0
k	0	0	0	0	0
l	0	0	0	0	0
m	$k+al$	0	0	0	l

* In relative form, $i = A:B+B:C+C:D+E:F+aF:G$, $j = A:C+B:D+aE:G$, $k = A:D$, $l = E:G$, $m = A:C+E:F+F:G$. [C. S. P.]

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[231212²]. The defining equation of this case is

$$c_{21} = 0.$$

This gives a quintuple algebra which may be called (ae_5), its multiplication table being *

(ae_5)	i	j	k	l	m
i	j	k	0	0	l
j	k	0	0	0	0
k	0	0	0	0	0
l	0	0	0	0	0
m	al	0	0	0	l

[2312²]. The defining equation of this case is

$$d_3 = 0.$$

There are two cases:

[2312²1], when c_{45} does not vanish;
[2312²], when c_{45} vanishes.

[2312²1]. The defining equation of this case can be reduced to

$$lm = k,$$

which gives

$$c_{45} = d_{21}^2 c_{45}, \quad d_{21}^2 = 1.$$

There are two cases:

[2312²1²], when $d_{21} = 1$;
[2312²12], when $d_{21} = -1$.

[2312²1²]. The defining equation of this case is

$$d_{21} = 1,$$

which gives

$$c_{54} = 1, \quad ml = k.$$

* In relative form, the same as (ad_5) except that $m = E:F + F:G$. [C. S. P.]

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There are two cases:

$[2312^{2}1^{2}]$, when c_{21} does not vanish;
$[2312^{2}1^{2}2]$, when c_{21} vanishes.

$[2312^{2}1^{2}]$. The defining equation of this case can be reduced to

$$c_{21} = 1.$$

This gives a quintuple algebra which may be called (af_5), its multiplication table being*

(af_5)	i	j	k	l	m
i	j	k	0	0	l
j	k	0	0	0	0
k	0	0	0	0	0
l	0	0	0	0	k
m	$k+l$	0	0	k	$j+ck$

---

*To show the construction of this algebra, we may substitute $i_1 = i + m$, $j_1 = 2j + (a+1)k + 2l$, $k_1 = 4k$, $l_1 = 2j + (a-1)k - 2l$, $m_1 = i - m$. This gives the following multiplication table:

	i	j	k	l	m
i	j	k	0	0	$-\frac{a-1}{4}k$
j	k	0	0	0	0
k	0	0	0	0	0
l	0	0	0	0	k
m	$-\frac{a+1}{4}k$	0	0	k	l

This algebra thus strongly resembles (ob_5). In relative form, $i = A:B + B:C + C:D + A:G - \frac{a+1}{4}G:D$, $j = A:C + B:D - \frac{a+1}{4}A:D$, $k = A:D$, $l = A:F + E:D - \frac{a-1}{4}A:D$, $m = A:E + E:F + F:D + A:G - \frac{a-1}{4}G:D$. [C. S. P.]

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[$2312^{2}1^{2}2$]. The defining equation of this case is

$$c_{11} = 0 .$$

There are two cases:

[$2312^{2}1^{2}21$], when c_{3} does not vanish;
[$2312^{2}1^{2}2^{2}$], when c_{3} vanishes.

[$2312^{2}1^{2}21$]. The defining equation of this case can be reduced to

$$c_{3} = 1 .$$

This gives a quintuple algebra which may be called (ag_{3}), its multiplication table being *

(ag_{3})	i	j	k	l	m
i	j	k	0	0	l
j	k	0	0	0	0
k	0	0	0	0	0
l	0	0	0	0	k
m	l	0	0	k	$j+k$

[$2312^{2}1^{2}2^{2}$]. The defining equation of this case is

$$c_{8} = 0 .$$

This gives a quintuple algebra which may be called (ah_{3}), its multiplication table being †

---

* On substituting $i_{1} = i + \frac{1}{2}j + m$. $m_{1} = i + \frac{1}{2}j - m$, this algebra falls apart into two of the form (b_{4}). [C. S. P.]

† On substituting $i_{1} = i + m$, $m_{1} = i - m$, $j_{1} = j + l$, $l_{1} = j - l$, this algebra falls apart into two of the form (b_{4}). [C. S. P.]

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(ah_3)	i	j	k	l	m
i	j	k	0	0	l
j	k	0	0	0	0
k	0	0	0	0	0
l	0	0	0	0	k
m	l	0	0	k	j

[2312²12]. The defining equation of this case is

$$d_{31} = -1,$$

which gives

$$c_{34} = -1, \quad ml = -k.$$

There are two cases:

[2312²121], when c_{31} does not vanish;
[2312²12²], when c_{31} vanishes.

[2312²121]. The defining equation of this case can be reduced to

$$c_{31} = 1.$$

This gives a quintuple algebra which may be called (ai_3), its multiplication table being *

(ai_3)	i	j	k	l	m
i	j	k	0	0	l
j	k	0	0	0	0
k	0	0	0	0	0
l	0	0	0	0	k
m	$k-l$	0	0	$-k$	$j+ek$

* In relative form, $i = A:C-B:F+C:E+D:G+E:G$, $j = A:E+C:G$, $k = A:G$, $= A:F-B:G$, $m = A:B+A:D+B:E+C:F+aD:G+F:G$. [C. S. P.]

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[$2312^{3}12^{3}$]. The defining equation of this case is

$$mi = -l.$$

There are two cases:

[$2312^{3}12^{3}1$], when c_3 does not vanish;
[$2312^{3}12^{3}$], when c_3 vanishes.

[$2312^{3}12^{3}1$]. The defining equation of this case can be reduced to

$$c_3 = 1.$$

This gives a quintuple algebra which may be called (aj_3), its multiplication table being*

(aj_3)	i	j	k	l	m
i	j	k	0	0	l
j	k	0	0	0	0
k	0	0	0	0	0
l	0	0	0	0	k
m	$-l$	0	0	$-k$	$j+k$

[$2312^{3}12^{3}$]. The defining equation of this case is

$$m^3 = j.$$

This gives a quintuple algebra which may be called (ak_3), its multiplication table being†

---

* In relative form, $i = A:C+C:E+E:G-B:F$, $j = A:E+C:G$, $k = A:G$, $l = A:F-B:G$, $m = A:B+B:E+C:F+F:G+A:D+D:G$. [C. S. P.]

† In relative form, $i = A:C+C:D+D:F-B:E$, $j = A:D+C:F$, $k = A:F$, $l = A:E-B:F$, $m = A:B+B:D+C:E+E:F$. [C. S. P.]

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(ak_s)	i	j	k	l	m
i	j	k	0	0	l
j	k	0	0	0	0
k	0	0	0	0	0
l	0	0	0	0	k
m	$-l$	0	0	$-k$	j

[2312^2]. The defining equations of this case are

$$ml = lm = 0, \quad m^3 = c_3 k.$$

There are two cases:

[2312^21], when d_{31} is not unity;
[2312^1], when d_{31} is unity.

[2312^21]. The defining equation of this case is

$$d_{31} \neq 1,$$

which gives

$$i[(1-d_{31})m - c_{31}j] = (1-d_{31})l - c_{31}k, \quad i[(1-d_{31})l - c_{31}k] = 0,$$
$$[(1-d_{31})l - c_{31}k]i = 0, \quad [(1-d_{31})m - c_{31}j]i = d_{31}[(1-d_{31})l - c_{31}k],$$
$$[(1-d_{31})l - c_{31}k][(1-d_{31})m - c_{31}j] = 0,$$
$$[(1-d_{31})m - c_{31}j][(1-d_{31})l - c_{31}k] = 0,$$
$$[(1-d_{31})m - c_{31}j]^3 = (1-d_{31})^3 c_3 k;$$

so that the substitution of $(1-d_{31})m - c_{31}j$ for m, and of $(1-d_{31})l - c_{31}k$ for l, is the same as to make

$$c_{31} = 0.$$

There are now two cases:

[2312^21^2], when c_3 does not vanish;
[2312^212], when c_3 vanishes.

[2312^21^2]. The defining equation of this case can be reduced to

$$m^3 = k.$$

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This gives a quintuple algebra which may be called (al_5), its multiplication table being *

(al_5)	i	j	k	l	m
i	j	k	0	0	l
j	k	0	0	0	0
k	0	0	0	0	0
l	0	0	0	0	0
m	dl	0	0	0	k

[2312^{5}12]. The defining equation of this case is

$$m^5 = 0.$$

This gives a quintuple algebra which may be called (am_5), its multiplication table being

(am_5)	i	j	k	l	m
i	j	k	0	0	l
j	k	0	0	0	0
k	0	0	0	0	0
l	0	0	0	0	0
m	dl	0	0	0	0

* In relative form, $i = A:B+B:C+C:D+dE:F$, $j = A:C+B:D$, $k = A:D$, $l = A:F$, $m = A:E+B:F+E:D$. [C. S. P.]

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[2312⁴]. The defining equation of this case is

$$d_{21} = 1 .$$

There are two cases:

[2312⁴1], when c_{21} does not vanish;
[2312⁵], when c_{21} vanishes.

[2312⁴1]. The defining equation of this case is easily reduced to

$$c_{21} = 1 .$$

There are two cases:

[2312⁴1²], when c_3 does not vanish;
[2312⁴12], when c_3 vanishes.

[2312⁴1²]. The defining equation of this case is easily reduced to

$$m^2 = k .$$

This gives a quintuple algebra which may be called (an_5), its multiplication table being *

(an_5)	i	j	k	l	m
i	j	k	0	0	l
j	k	0	0	0	0
k	0	0	0	0	0
l	0	0	0	0	0
m	$l+k$	0	0	0	k

[2312⁴12]. The defining equation of this case is

$$m^2 = 0 .$$

This gives a quintuple algebra which may be called (ao_5), its multiplication table being †

* In relative form, $i = A:E+A:B+B:C+C:D+E:F$, $j = A:C+B:D+A:F$, $k = A:D$, $l = A:F$, $m = A:C+A:E+E:D$. [C. S. P.]

† In relative form, $i = A:B+B:C+C:D+E:F$, $j = A:C+B:D$, $k = A:D$, $l = A:F$, $m = A:C+A:E+B:F$. [C. S. P.]

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(ao_5)	i	j	k	l	m
i	j	k	0	0	l
j	k	0	0	0	0
k	0	0	0	0	0
l	0	0	0	0	0
m	$l+k$	0	0	0	0

[2312^5]. The defining equation of this case is

$$mi = l.$$

There are two cases:

[2312^{5}2], when c_5 does not vanish;

[2312^5], when c_5 vanishes.

[2312^{5}1]. The defining equation of this case can be reduced to

$$m^5 = k.$$

This gives a quintuple algebra which may be called (ap_5), its multiplication table being*

(ap_5)	i	j	k	l	m
i	j	k	0	0	l
j	k	0	0	0	0
k	0	0	0	0	0
l	0	0	0	0	0
m	l	0	0	0	k

*In relative form, $i = A:B+B:C+C:D+E:F$, $j = A:C+B:D$, $k = A:D$, $l = A:F$, $m = A:E+B:F+E:D$. [C. S. P.]

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[2312$^{\alpha}$]. The defining equation of this case is

$$m^3 = 0.$$

This gives a quintuple algebra which may be called (aq_5), its multiplication table being

(aq_5)	i	j	k	l	m
i	j	k	0	0	l
j	k	0	0	0	0
k	0	0	0	0	0
l	0	0	0	0	0
m	l	0	0	0	0

[232]. The defining equation of this case is

$$im = 0,^*$$

which gives

$$0 = jm = km,$$

and it may be assumed that

$$li = 0.$$

This gives

$$lj = lk = 0 = i l^n = l^n i = ilm = iml = mli = im.$$

There are two cases:

[2321], when $mi = l$;
[232$^{\beta}$], when $mi = 0$.

[2321]. The defining equation of this case is

$$mi = l,$$

which gives

$$0 = mj = mk, \quad lm = e_{45}k + d_{45}l + e_{45}m,$$
$$lmi = l^3 = e_{45}l, \quad 0 = l^4 = e_{45}l^2 = e_{45} = l^3, \quad m^3 = e_5 k + d_5 l + e_5 m,$$
$$m^2 i = ml = e_5 l, \quad 0 = m^4 l = e_5 m^2 l = e_5 = ml; \quad 0 = lm^3 = d_{45} lm = d_{45}.$$

* What is meant is that every quantity not involving powers of i is nilfaciend with reference to i. Hence, $i\alpha = 0$, also. [C. S. P.]

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There are two cases:

[2321^2], when c_{45} does not vanish;
[23212], when c_{45} vanishes.

[2321^2]. The defining equation of this case can be reduced to

$$lm = k,^*$$

which gives

$$m^3 = c_3 k, \quad (m - c_3 l)^3 = 0,$$

so that the substitution of $m - c_3 l$ for m is the same as to make

$$c_3 = 0.$$

This gives a quintuple algebra which may be called (ar_3), of which the multiplication table is

(ar_3)	i	j	k	l	m
i	j	k	0	0	0
j	k	0	0	0	0
k	0	0	0	0	0
l	0	0	0	0	k
m	l	0	0	0	0

[23212]. The defining equation of this case is

$$lm = 0.$$

There are two cases:

[232121], when d_3 does not vanish;
[23212^2], when d_3 vanishes.

[232121]. The defining equation of this case can be reduced to

$$d_3 = 1.$$

There are two cases:

[232121^2], when c_2 does not vanish;
[2321212], when c_2 vanishes.

[232121^2]. The defining equation of this case can be reduced to

$$c_2 = 1.$$

* But $0 = im = mim = lm$. Thus, this case disappears, and the algebra (ar_3) is incorrect. [C. S. P.]

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This gives a quintuple algebra which can be called (as_5), its multiplication table being*

(as_5)	i	j	k	l	m
i	j	k	0	0	0
j	k	0	0	0	0
k	0	0	0	0	0
l	0	0	0	0	0
m	l	0	0	0	$k+l$

[2321212]. The defining equation of this case is

$$c_5 = 0\,.$$

This gives a quintuple algebra which may be called (at_5), its multiplication table being

(at_5)	i	j	k	l	m
i	j	k	0	0	0
j	k	0	0	0	0
k	0	0	0	0	0
l	0	0	0	0	0
m	l	0	0	0	l

[23212^2]. The defining equation of this case is

$$m^2 = c_5 k\,.$$

There are two cases:

[23212^{2}1], when c_5 does not vanish;

[23212^2], when c_5 vanishes.

* In relative form, $i = A:B+B:C+C:D+E:F$. $j = A:C+B:D$. $k = A:D$. $l = A:F$, $m = A:E+E:F+E:D$. Omitting the last term of m, we have (at_5). [C. S. P.]

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[$2321^2 1$]. The defining equation of this case can be reduced to

$$m^3 = k.$$

This gives a quintuple algebra which may be called (au_5), its multiplication table being*

(au_5)	i	j	k	l	m
i	j	k	0	0	0
j	k	0	0	0	0
k	0	0	0	0	0
l	0	0	0	0	0
m	l	0	0	0	k

[2321^3]. The defining equation of this case is

$$m^3 = 0.$$

This gives a quintuple algebra which may be called (av_5), its multiplication table being

(av_5)	i	j	k	l	m
i	j	k	0	0	0
j	k	0	0	0	0
k	0	0	0	0	0
l	0	0	0	0	0
m	l	0	0	0	0

*In relative form, $i = A:B + B:C + C:D$, $j = A:C + B:D$, $k = A:D$, $l = E:D$, $m = E:C + A:F + F:D$. The omission of the last two terms of m gives (av_5). [C. S. P.]

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[232[1]]. The defining equation of this case is

$$mi = 0,$$

which gives

$$0 = mj = mk = lmi = m^3 i,$$

and there is no pure algebra in this case.

[24]. The defining equation of this case is

$$i^3 = 0,$$

and by § 59,

$$i^3 = j, \quad ij = ji = j^2 = 0.$$

There are three cases:

[241], when $ik = l$, $il = m$;
[242], when $ik = l$, $il = im = 0$;
[243], when $ik = il = im = 0$.

[241]. The defining equations of this case are

$$ik = l, \quad il = m,$$

which give

$jk = m$, $\quad im = jl = jm = 0$, $\quad 0 = iml = mi^3 = e_{34}mi^3 = e_{34}$, $\quad jk = m$,
$il^3 = ml = b_{34}j$, $\quad l^3 = b_{34}i + b_4 j + e_4 m$, $\quad 0 = l^3 = b_{34}m + e_4 ml = b_{34} = ml$,
$im^3 = 0$. $\quad m^3 = b_3 j + e_3 m$, $\quad 0 = m^4 = e_3 m^3 = e_3$,
$imi = 0$, $\quad mi = b_{31}j + e_{31}m$, $\quad mj = e_{31}mi$, $\quad mi^3 = 0 = e_{31}$,
$ili = mi = b_{31}j$, $\quad li = b_{31}i + b_{43}j + e_{31}m$,
$lil = lm = b_{31}m$, $\quad 0 = l^3 m = b_{31} = lm = mi = mil = m^3$, $\quad (li)i = lj$,
$ik^2 = lk = a_3 j + c_3 l + d_3 m$, $\quad ilk = mk = c_3 m$, $\quad lik = l^3 = a_{31}m$,
$0 = mk^2 = c_3^2 m = c_3 = mk = k^2 m$,
$kj = ki^3 = a_{31}j + d_{31}li = a_{31}(1 + d_{31})j + d_{31}^2 m$,
$kil = km = a_{31}(1 + d_{31})m$, $\quad 0 = k^2 m = a_{31}(1 + d_{31})km = a_{31}(1 + d_{31}) = km$,
$kj = d_{31}^2 m$, $\quad 0 = k^3 = a_3 l + b_3 m + d_3 lk = a_3 = b_3 + d_3^2 = b_3 kj + d_3 kl$,
$kl = a_{31}l + (b_{31} + d_3 d_{31})m$, $\quad 0 = klk = a_{31}lk = d_3 a_{31} = lkl = a_{31}l^3 = a_{31} = l^3$,
$0 = d_3^2 a_{31} = b_{31}d_3 + d_3^2 d_{31} + b_3 l_{31}^2$,
* $0 = ki^3 + iki + i^3 k = (d_{31}^2 + d_{31} + 1)m$, $\quad d_{31} = \sqrt[3]{1} = \mathfrak{r}$,
$0 = k^2 i + kik + ik^2 = b_{31} + d_3(1 + 2d_{31})$, $\quad i(k + \rho i) = l + \rho j$, $\quad i(l + \rho j) = m$,
$(k + \rho i)i = b_{31}j + d_{31}l + e_{31}m + \rho j = (b_{31} + \rho - \rho d_{31})j + d_{31}(l + \rho j) + e_{31}m$,
$(l + \rho j)i = d_{31}m$,

* This line and the first equation of the next can be derived from $0 = (i + \rho k)^3$. [C. S. P.]

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so that if p satisfies the equation

$$p(d_{21} - 1) = b_{21},$$

the substitution of $k + pi$ for k and of $l + pj$ for l is the same as to make

$$0 = b_{21} = d_3 = b_3.$$

There are four cases:

[241²], when neither e_{21} nor e_3 vanishes;
[2412], when e_{21} does not vanish but e_3 vanishes;
[2413], when e_{21} vanishes and not e_3;
[2414], when e_{21} and e_3 both vanish.

[241²]. The defining equations of this case can be reduced, without loss of generality, to

$$e_{21} = e_3 = 1.$$

We thus obtain a quintuple algebra which may be called (av_5), its multiplication table being*

(av_5)	i	j	k	l	m
i	j	0	l	m	0
j	0	0	m	0	0
k	$\mathfrak{r}l + m$	$\mathfrak{r}^2 m$	m	0	0
l	$\mathfrak{r}m$	0	0	0	0
m	0	0	0	0	0

[2412]. The defining equations of this case can be reduced to

$$e_{21} = 1, \quad e_3 = 0.$$

* In relative form $i = A:B + B:D + \mathfrak{r}C:E + \mathfrak{r}E:F + G:F$, $j = A:D + \mathfrak{r}^2 C:F$, $k = A:C + B:E + D:F + A:G + G:F$, $l = A:E + B:F$, $m = A:F$. To obtain (av_4), omit the last term of k. To obtain (av_3), omit, instead, the last term of i. To obtain (av_2), omit both these last terms. [C. S. P.]

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We thus obtain a quintuple algebra which may be called (ax_3), its multiplication table being

(ax_3)	i	j	k	l	m
i	j	0	l	m	0
j	0	0	m	0	0
k	$\mathfrak{r}l+m$	$\mathfrak{r}^2m$	0	0	0
l	$\mathfrak{r}m$	0	0	0	0
m	0	0	0	0	0

[2413]. The defining equations of this case can be reduced to

$$e_3 = 0, \quad e_3 = 1.$$

We thus obtain a quintuple algebra which may be called (ay_3), its multiplication table being

(ay_3)	i	j	k	l	m
i	j	0	l	m	0
j	0	0	m	0	0
k	$\mathfrak{r}l$	$\mathfrak{r}^2m$	m	0	0
l	$\mathfrak{r}m$	0	0	0	0
m	0	0	0	0	0

[2414]. The defining equations of this case are

$$e_3 = e_3 = 0.$$

We thus obtain a quintuple algebra which may be called (az_3), its multiplication table being

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(az_5)	i	j	k	l	m
i	j	0	l	m	0
j	0	0	m	0	0
k	εl	$\varepsilon^2 m$	0	0	0
l	εm	0	0	0	0
m	0	0	0	0	0

[242]. The defining equations of this case are

$$ik = l, \quad il = im = 0,$$

which give

$$0 = jk = jl = jm,$$
$$li = iki = a_{31}j + e_{31}l, \quad 0 = l^2 = e_{31} = l^2 = lj,$$
$$0 = a_{31}jk = lik = l^2 = ikl = a_{34} = e_{34},$$
$$ik^2 = lk = a_3 j + e_3 l, \quad 0 = il^2 = li^2 = e_3 lk = e_3,$$
$$0 = imi = a_{31} = e_{31}, \quad mi^2 = mj = d_{31}li + e_{31}mi, \quad 0 = mji = e_{31},$$
$$mj = a_{31}d_{31}j, \quad 0 = m^2 j = a_{31}d_{31} = mj,$$
$$ikm = lm = a_{35}j + e_{35}l, \quad 0 = lm^2 = e_{35},$$
$$0 = i^2 k + iki + ki^2 = e_{31}d_{31} = 2a_{31} + a_{31}d_{31} + e_{31}b_{31},$$
$$kj = -a_{31}j, \quad 0 = k^2 j = a_{31} = kj = li = e_{31}b_{31},$$
$$0 = imk = a_{33} = e_{33}, \quad 0 = mk^2 = e_{33},$$
$$mik = ml = a_3 d_{31}j, \quad kik = kl = (a_3 l_{31} + e_{31}b_{33})j + e_{31}d_{33}l, \quad e_{34} = 0,$$
$$0 = k^2 l = e_{31}d_{33} = lki = e_{31}lm = e_{31}a_{35} = k^2 m = e_{35}.$$

There are two cases:

[2421], when e_{31} does not vanish;
[242^2], when e_{31} vanishes.

[2421]. The defining equation of this case can be reduced to

$$ki = m,$$

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which, by the aid of the above equations, gives

$$0 = mi = kil = ml = kim = m^2, \quad a_3 j = il^2 = k^2 i = lk = km, \quad 0 = lm,$$
$$b_{32} j = kik = kl = mk, \quad 0 = ik^2 + kik + k^2 i = 2a_3 + b_{32},$$
$$0 = k^3 = a_3 = b_{32} = kl = km = mk = ml;$$

and if p is determined by the equation

$$p^2 + (d_3 + e_3)\, p - b_3 = 0,$$

$k + pi$, $l + pj$, and $m + pj$ can be respectively substituted for k, l and m, which is the same thing as to make

$$b_3 = 0.$$

There are three cases:

[2421^2], when neither d_3 nor e_3 vanishes;
[24212], when d_3 vanishes and not e_3;
[24213], when d_3 and e_3 both vanish.

[2421^2]. The defining equation of this case can be reduced to

$$d_3 = 1.$$

This gives a quintuple algebra which may be called (ba_3), its multiplication table being*

(ba_3)	i	j	k	l	m
i	j	0	l	0	0
j	0	0	0	0	0
k	m	0	$l + em$	0	0
l	0	0	0	0	0
m	0	0	0	0	0

* In relative form, $i = A:B + B:C + A:E$, $j = A:C$, $k = D:B + E:F + D:G + eG:C + A:E$, $l = A:F$, $m = D:C$. By omitting the last term of k and putting $e = 1$ we get (bb_3), and by omitting the last two terms of k we get (bc_3). [C. S. P.]

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[2421²]. The defining equation of this case can be reduced to

$$k^2 = m .$$

This gives a quintuple algebra which may be called (bb_3), its multiplication table being

(bb_3)	i	j	k	l	m
i	j	0	l	0	0
j	0	0	0	0	0
k	m	0	m	0	0
l	0	0	0	0	0
m	0	0	0	0	0

[24213]. The defining equation of this case is

$$k^2 = 0 .$$

This gives a quintuple algebra which may be called (bc_3), its multiplication table being

(bc_3)	i	j	k	l	m
i	j	0	l	0	0
j	0	0	0	0	0
k	m	0	0	0	0
l	0	0	0	0	0
m	0	0	0	0	0

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[242²]. The defining equation of this case is

$$e_{21} = 0.$$

There are two cases:

[242²1], when e_3 does not vanish;
[242²], when e_2 vanishes.

[242²1]. The defining equation of this case can be reduced to

$$k^3 = a_3 i + m,$$

which gives

$$kik = kl = a_3 d_{21} j, \quad ik^3 = lk = a_3 j, \quad k^2 i = a_3 j + mi = d_{21} kl = a_3 d_{21}^2 j,$$
$$0 = k^2 i + ik + kik = a_3(d_{21}^2 + d_{21} + 1), \quad mi = a_3(d_{21} l - 1) j, \quad ml = mik = 0,$$
$$0 = k^3 = a_3 l + mk = a_3 ki + km,$$
$$mk = -a_3 l, \quad km = -a_3 b_{21} j - a_3 d_{21} l, \quad lm = 0.$$

There are two cases:

[242²1³], when a_3 does not vanish;
[242³12], when a_3 vanishes.

[242²1³]. The defining equation of this case can be reduced to

$$k^3 = i + m,$$

which gives

$$d_{21} = \sqrt[3]{1} = \mathfrak{r}, \quad lk = j, \quad mk = -l,$$
$$ki = -km = b_{21} j + \mathfrak{r} l, \quad mi = (\mathfrak{r}^2 - 1) j, \quad m^3 = -\mathfrak{r} j.$$

There are two cases:

[242²1³], when b_{21} does not vanish;
[242³1²2], when b_{21} vanishes.

[242²1³]. The defining equation of this case can be reduced to

$$ki = j + \mathfrak{r} l.$$

This gives a quintuple algebra which may be called $(b d_5)$, its multiplication table being *

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* In relative form, $i = A:D + D:F + B:E + C:F$, $j = A:F$, $k = \mathfrak{r}A:B + \mathfrak{r}B:C + D:E - \frac{1}{\mathfrak{r}} D:F + E:F$, $l = A:E - \frac{1}{\mathfrak{r}} A:F + B:F$, $m = \mathfrak{r}^1 A:C - A:D - B:E - C:F$. [C. S. P.]

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(bd_5)	i	j	k	l	m
i	j	0	l	0	0
j	0	0	0	0	0
k	$j+\mathfrak{r}l$	0	$i+m$	$\mathfrak{r}j$	$-j-\mathfrak{r}l$
l	0	0	j	0	0
m	$(\mathfrak{r}^3-1)j$	0	$-l$	0	$-\mathfrak{r}^2j$

[242^{2}1^{2}2]. The defining equation of this case is

$$ki=\mathfrak{r}l.$$

This gives a quintuple algebra which may be called (be_5), its multiplication table being*

(be_5)	i	j	k	l	m
i	j	0	l	0	0
j	0	0	0	0	0
k	$\mathfrak{r}l$	0	$i+m$	$\mathfrak{r}j$	$-\mathfrak{r}l$
l	0	0	j	0	0
m	$(\mathfrak{r}^3-1)j$	0	$-l$	0	$-\mathfrak{r}^2j$

[242^{2}12]. The defining equation of this case is

$$k^2=m,$$

which gives

$$0=kl=lk=km=mk=m^2=k^2i=mi.$$

There are two cases:

[242^{2}121], when b_{21} does not vanish;
[242^{2}12^2], when b_{21} vanishes.

* On adding to the expression for k in the last note the term $-A:C$, we have this algebra in relative form. [C. S. P.]

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[242²121]. The defining equation of this case can be reduced to

$$ki = j + d_{31}l.$$

This gives a quintuple algebra which may be called (bf_5), its multiplication table being *

(bf_5)	i	j	k	l	m
i	j	0	l	0	0
j	0	0	0	0	0
k	$j+dl$	0	m	0	0
l	0	0	0	0	0
m	0	0	0	0	0

[242²12³]. The defining equation of this case is

$$ki = d_{31}l.$$

This gives a quintuple algebra which may be called (bg_5), its multiplication table being †

(bg_5)	i	j	k	l	m
i	j	0	l	0	0
j	0	0	0	0	0
k	dl	0	m	0	0
l	0	0	0	0	0
m	0	0	0	0	0

* In relative form, $i = A:B+B:C+D:E$, $j = A:C$, $k = A:B+dA:D+B:E+B:F$, $l = A:E$, $m = A:E+A:F$. [C. S. P.]

† In relative form, $i = A:B+B:C+D:E$, $j = A:C$, $k = dA:D+B:E+B:F$, $l = A:E$, $m = A:F$. The algebra (ar_5) is what this becomes when $d = 0$. [C. S. P.]

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[242³]. The defining equation of this case is

$$e_3 = 0\,,$$

which gives *

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* It is not easy to see how the author proves that $a_3 = 0$. But it can be proved thus. $0 = k^2 = (a_1 i + b_1 j + d_1 l)k = a_1 l + a_1 d_1 j$.

The algebras of the case [242²] are those quintuple systems in which every product containing j or l as a factor vanishes, while every product which does not vanish is a linear function of j and l. Any multiplication table conforming to these conditions is self-consistent, but it is a matter of some trouble to exclude every case of a *mixed* algebra. An algebra of the class in question is separable, if all products are similar. But this case requires no special attention; and the only other is when two dissimilar expressions U and V can be found, such that both being linear functions of i, k and m, $UV - VU = 0$. It will be convenient to consider separately, first, the conditions under which $UV - VU = 0$, and, secondly, those under which $UV + VU = 0$. To bring the subjects under a familiar form, we may conceive of i, k, m as three vectors not coplanar, so that, writing

$$U = xi + yk + zm\,, \qquad V = x'i + y'k + z'm\,,$$

we have x, y, z, and x', y', z', the Cartesian coördinates of two points in space. [We might imagine the space to be of the hyperbolic kind, and take the coefficients of j and l as coördinates of a point on the quadric surface at infinity. But this would not further the purpose with which we now introduce geometric conceptions.] But since we are to consider only such properties of U and V as belong equally to all their numerical multiples, we may assume that they always lie in any plane

$$Ax + By + Cz = 1\,,$$

not passing through the origin; and then x, y, z, and x', y', z', will be the homogeneous coördinates of the two points U and V in that plane. Let it be remembered that, although i, k, m are vectors, yet their multiplication does not at all follow the rule of quaternions, but that

$$\begin{array}{lll} i^2 = b_{11} j + d_{11} l\,, & ik = b_{11} j + d_{11} l\,, & im = b_{13} j + d_{13} l\,. \\ ki = b_{11} j + d_{11} l\,. & k^2 = b_{22} j + d_{22} l\,, & km = b_{23} j + d_{23} l\,. \\ mi = b_{13} j + d_{13} l\,. & mk = b_{23} j + d_{23} l\,. & m^2 = b_{33} j + d_{33} l\,. \end{array}$$

The condition that $UV - VU = 0$ is expressed by the equations

$$\begin{aligned} &(b_{11} - b_{11})(xy' - x'y) + (b_{12} - b_{12})(xz' - x'z) + (b_{13} - b_{13})(yz' - y'z) = 0\,, \\ &(d_{11} - d_{11})(xy' - x'y) + (d_{12} - d_{12})(xz' - x'z) + (d_{13} - d_{13})(yz' - y'z) = 0\,. \end{aligned}$$

The first equation evidently signifies that for every value of U, V must be on a straight line, that this line passes through U, and that it also passes through the point

$$P = (b_{12} - b_{12})\,i + (b_{11} - b_{13})\,k + (b_{12} - b_{13})\,m\,.$$

The second equation expresses that the line between U and V contains the point

$$Q = (d_{12} - d_{12})\,i + (d_{11} - d_{13})\,k + (d_{12} - d_{13})\,m\,.$$

The two equations together signify, therefore, that U and V may be any two points on the line between the fixed points P and Q. Linear transformations of j and l may shift P and Q to any other situations on the line joining them, but cannot turn the line nor bring the two points into coincidence.

The condition that $UV + VU = 0$ is expressed by the equations

$$\begin{aligned} &2b_{11}xx' + 2b_{12}yy' + 2b_{13}zz' + (b_{12} + b_{12})(xy' + x'y) + (b_{13} + b_{13})(xz' + x'z) + (b_{23} + b_{23})(yz' + y'z) = 0\,, \\ &2d_{11}xx' + 2d_{12}yy' + 2d_{13}zz' + (d_{12} + d_{12})(xy' + x'y) + (d_{13} + d_{13})(xz' + x'z) + (d_{23} + d_{23})(yz' + y'z) = 0\,. \end{aligned}$$

The first of these evidently signifies that for any position of V the locus of U is a line; that U being fixed at any point on that line, V may be carried to any position on a line passing through its original position: and that further, if U is at one of the two points where its line cuts the conic

$$b_{11}x^2 + b_{22}y^2 + b_{33}z^2 + (b_{12} + b_{12})\,xy + (b_{13} + b_{13})\,xz + (b_{23} + b_{23})\,yz = 0\,,$$

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$$0 = k^2 i = a_3 j = a_5 = lk = ml = kl = m^3 = e_5 = d_5 a_{25} = k^2 m = e_{25},$$
$$0 = kmk = a_{25} l = a_{25} = lm.$$

then V may be at an infinitely neighboring point on the same conic, so that tangents to the conic from V cut the locus of U at their points of tangency. The second equation shows that the points U and V have the same relation to the conic

$$d_1 x^2 + d_2 y^2 + d_3 z^2 + (d_{12} + d_{21})\, xy + (d_{13} + d_{31})\, xz + (d_{23} + d_{32})\, yz = 0.$$

These conics are the loci of points whose squares contain respectively no term in j and no term in l. Their four intersections represent expressions whose squares vanish. Hence, linear transformations of j and l will change these conics to any others of the sheaf passing through these four fixed points. The two equations together, then, signify that through the four fixed points, two conics can be drawn tangent at U and V to the line joining these last points.

Uniting the conditions of $UV - VU = 0$ and $UV + VU = 0$, they signify that U and V are on the line joining P and Q at those points at which this line is tangent to conics through the four fixed points whose squares vanish. But if the algebra is pure, it is impossible to find two such points; so that the line between P and Q must pass through one of the four fixed points. In other words, the necessary condition of the algebra being pure is that one and only one nilpotent expression in i, k, m, should be a linear function of P and Q.

The two points P and Q together with the two conics completely determine all the constants of the multiplication table. Let S and T be the points at which the two conics separately intersect the line between P and Q. A linear transformation of j will move P to the point $pP + (1-p)\,Q$ and will move S to the point $pS + (1-p)\,T$, and a linear transformation of l will move Q and T in a similar way. The points P and S may thus be brought into coincidence, and the point Q may be brought to the common point of intersection of the two conics with the line from P to Q. The geometrical figure determining the algebra is thus reduced to a first and a second conic and a straight line having one common intersection. This figure will have special varieties due to the coincidence of different intersections, etc.

There are six cases: [1], there is a line of quantities whose squares vanish and one quantity out of the line; [2], there are four dissimilar quantities whose squares vanish; [3], two of these four quantities coincide; [4], two pairs of the four quantities coincide; [5], three of the four quantities coincide; [6], all the quantities coincide.

We may, in every case, suppose the equation of the plane to be $x + y + z = 1$.

[1]. In this case, the line common to the two conics may be taken as $y = 0$, and the separate lines of the conics as $x = 0$ and $z = 0$, respectively. We may also assume $2P = x + y$ and $2Q = x + z$. We thus obtain the following multiplication table, where the rows and columns having j and l as their arguments are omitted:

	i	k	m
i	0	$2l$	$-j$
k	$-l$	0	$3j+l$
m	j	$l-j$	0

[2]. In this case, we may take k as the common intersection of the two conics and the line, i, m, and $i - k + m$ as the other intersections of the conics. We have $Q = k$, and we may write

$$P = S = pi + (1-p-q)k + qm, \qquad T = rP + (1-r)Q = rpi + (1-rp-rq)k + rqm.$$

We thus obtain the following multiplication table:

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There are two cases:

[242²1], when d_3 does not vanish;
[242¹], when d_3 vanishes.

[242²1]. The defining equation of this case can be reduced to

$$d_3 = 1,$$

which gives

$$i(k + b_3 i + pm) = l + b_3 j = m^3;$$

and if

$$l^3 = -d_2 - b_3 - b_3 d_{21} - b_3 l d_{31} - p d_{32} - p l d_{33},$$

	i	k	m
i	0	$q(q+1)j + rq(rq-1)l$	$[-2-p(p-3)+q(q+1)]j + (-3-rp(rp-1)+rq(rq-1)]l$
k	$q(q-3)j + rq(rq-1)l$	0	$-p(p-3)j - rp(rp-1)l$
m	$[2-p(p+1)+q(q-3)]j + [2-rp(rp-1)+rq(rq-1)]l$	$-p(p+1)j - rp(rp-1)l$	0

[3]. Let k be the double point common to the two conics, and let i and m be their other intersections. Then all expressions of the form $ku + uk$ are similar. The line between P and Q cannot pass through k, because in that case all products would be similar. We may therefore assume that it passes through i. Then, we have $Q = i$, we may assume $S = P = i - k + m$, and we may write $T = rP + (1-r)Q = i - rk + rm$. The equation of the common tangent to the conics at k may be written $hx + (1-h)z = 0$. Then the equations of the two conics are

$$hxy + xz + (1-h)yz = 0,$$
$$hxy + (h + r - hr)xz + (1-h)yz = 0.$$

We thus obtain the following multiplication table:

	i	k	m
i	0	$(h+1)j + (h+r)l$	$2j + [h(1-r)+2r]l$
k	$(h-1)j + (h-r)l$	0	$(2-h)(j+l)$
m	$h(1-r)l$	$-h(j+l)$	0

[4]. In this case we may take i and m as the two points of contact of the conics, k as P, and $i - k + m$ as T. Then writing the equations of the two tangents

$$yy + z = 0. \qquad x + hy = 0.$$

the two conics become

$$gxy + xz + hyz = 0.$$
$$(g + h - 1)y^2 + gxy + xz + hyz = 0.$$

and the multiplication table is as follows:

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the substitution of $k + b_3 i + pm$ for k and $l + b_3 j$ for l is the same as to make

$$b_3 = d_3 = 0 .$$

This gives

$$m^2 = l, \quad k^2 = b_2 j .$$

There are two cases:

[242²1²], when b_2 does not vanish;
[242²12], when b_2 vanishes.

[242²1²]. The defining equation of this case can be reduced to

$$k^2 = j .$$

	i	k	m
i	$(g+h-1)\,l$	$gj+(g+1)\,l$	$2l$
k	$gj+(g-1)\,l$	0	$hj+(h+1)\,l$
m	$2j$	$hj+(h-1)\,l$	0

[5]. In this case, we may take k as the point of osculation of the conics and i as their point of intersection. The line between P and Q must either, [51], pass through k, or, [52], pass through i.

[51]. We may, without loss of generality, take

$$P = k, \quad Q = m ,$$

and the equations of the two conics are

$$z^2 + rxz = 0, \quad rxy + 2qxz + 2yz = 0 .$$

Then, the multiplication table is as follows:

	i	k	m
i	0	0	ql
k	rl	0	l
m	$rj+ql$	l	j

[52]. We have $Q = i$, we may take $T = m$, and we may assume $P = 2i - m$ and $b_{12} + b_{11} = 1$. Then, we may write the equations of the two conics,

$$2z^2 + xy + xz + ryz = 0 ,$$
$$-rxy + (2-r)\,xz + r^2 yz = 0 .$$

We thus obtain the following multiplication table:

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This gives a quintuple algebra which can be called (bh_5), its multiplication table being *

(bh_5)	i	j	k	l	m
i	j	0	l	0	0
j	0	0	0	0	0
k	$aj+bl$	0	j	0	$cj+dl$
l	0	0	0	0	0
m	$a'j+b'l$	0	$c'j+d'l$	0	l

	i	k	m
i	0	$-rl$	$j-(r-2)l$
k	$2j-rl$	0	$(r-2)j+(r^2+1)l$
m	$j-(r-2)l$	$(r-2)j+(r^2-1)l$	$2j$

[6]. The conics have but one point in common. This may be taken at k. We have $Q=k$, we may take $T=i$ and $2P=2S=i+k$. We may also take $b_1=-1$. Then the equations of the two conics may be written

$$-x^2+pz^2+2xy+4qxz+2ryz=0,$$
$$(4+pr^2)z^2+2xy+4(q+r)xz+2ryz=0.$$

We thus find this multiplication table:

	i	k	m
i	$-j$	$j+l$	$(2q-1)j+2(q+r-p)l$
k	$j+l$	0	$(r+1)j+rl$
m	$(2q+1)+2(q+r+p)l$	$(r-1)j+rl$	$pj+(4+pr^2)l$

If this analysis is correct, only three indeterminate coefficients are required for the multiplication tables of this class of algebras. [C. S. P.]

* See last note. I do not give relative forms for this class of algebras, owing to the extreme ease with which they may be found. [C. S. P.]

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[242^{3}12]. The defining equation of this case is

$$k^2 = 0.$$

There are two cases:

[242^{3}121], when b_{21} does not vanish;
[242^{3}12^2], when b_{21} vanishes.

[242^{3}121]. The defining equation of this case can be reduced to

$$b_{21} = 1.$$

This gives a quintuple algebra which may be called (bi_5), its multiplication table being

(bi_5)	i	j	k	l	m
i	j	0	l	0	0
j	0	0	0	0	0
k	$j+al$	0	0	0	$bj+cl$
l	0	0	0	0	0
m	$a'j$ $+b'l$	0	$c'j$ $+d'l$	0	l

[242^{3}12^2]. The defining equation of this case is

$$ki = d_{21}l.$$

There are two cases:

[242^{3}12^{2}1], when b_{21} does not vanish;
[242^{3}12^3], when b_{21} vanishes.

[242^{3}12^{2}1]. The defining equation of this case can be reduced to

$$b_{21} = 1.$$

This gives a quintuple algebra which may be called (bj_5), its multiplication table being

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(bj_5)	i	j	k	l	m
i	j	0	l	0	0
j	0	0	0	0	0
k	al	0	0	0	$bj+cl$
l	0	0	0	0	0
m	$j+a'l$	0	$b'j+il$	0	l

[$242^2 12^3$]. The defining equation of this case is

$$mi = d_{51}l;$$

which can always, in the case of a pure algebra, be reduced to

$$mi = l.$$

This gives a quintuple algebra which may be called (bk_5), its multiplication table being

(bk_5)	i	j	k	l	m
i	j	0	l	0	0
j	0	0	0	0	0
k	al	0	0	0	$bj+cl$
l	0	0	0	0	0
m	l	0	$a'j$ $+b'l$	0	l

[242^1]. The defining equation of this case is

$$m^2 = b_5 j,$$

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and it can be reduced to [242³1] unless

$$d_{31} = d_3 = 0\,, \quad k^2 = b_3 j\,, \quad d_{31} = -1\,, \quad d_{35} = -d_{33}\,;$$

whence it may be assumed that

$$mi = j\,;$$

and since

$$(k + bi)^3 = 0\,,$$

when

$$p^2 + pb_{31} + b_3 = 0\,,$$

it may also be assumed that

$$k^2 = 0\,.$$

There are two cases:

[242⁴1], when b_{31} does not vanish;
[242⁵], when b_{31} vanishes.

[242⁴1]. The defining equation of this case can be reduced to

$$b_{31} = 1\,.$$

This gives a quintuple algebra which may be called (bl_3), its multiplication table being

(bl_3)	i	j	k	l	m
i	j	0	l	0	0
j	0	0	0	0	0
k	$j-l$	0	0	0	$aj+bl$
l	0	0	0	0	0
m	j	0	$aj+bl$	0	cj

[242⁵]. The defining equation of this case is

$$ki = -l.$$

There are two cases:

[242⁵1], when b_{35} does not vanish;
[242⁶], when b_{35} vanishes.

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[242⁵1]. The defining equation of this case can be reduced to

$$b_{25} = 1 .$$

This gives a quintuple algebra which may be called (bm_5), its multiplication table being*

(bm_5)	i	j	k	l	m
i	j	0	l	0	0
j	0	0	0	0	0
k	$-l$	0	0	0	$j+al$
l	0	0	0	0	0
m	j	0	$bj-al$	0	cj

[242⁶]. The defining equation of this case is

$$b_{35} = 0 .$$

There are two cases:

[242⁶1], when b_{53} does not vanish;
[242⁷], when b_{53} vanishes.

[242⁶1]. The defining equation of this case can be reduced to

$$b_{53} = 1 .$$

This gives a quintuple algebra which may be called (bn_5), its multiplication table being†

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* This algebra is mixed. Namely, if $b \neq 1$, it separates on substituting $i_1 = (1-b)\,i + k$, $k_1 = (1-b)\,i + [a(1-b)+1]\,k - (1-b)^2 m$; but if $b = 1$, it separates on substituting $i_1 = ai - (a^2 + a + c)\,k + m$, $k_1 = ai + qk + m$. [C. S. P.]

† Substitute $i_1 = i - k$, $k_1 = ak + m$, and the algebra separates. [C. S. P.]

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(bn_5)	i	j	k	l	m
i	j	0	l	0	0
j	0	0	0	0	0
k	$-l$	0	0	0	al
l	0	0	0	0	0
m	j	0	$j-al$	0	cj

[242']. The defining equation of this case is

$$b_{33} = 0.$$

This gives a quintuple algebra which may be called (bo_5), its multiplication table being*

(bo_5)	i	j	k	l	m
i	j	0	l	0	0
j	0	0	0	0	0
k	$-l$	0	0	0	al
l	0	0	0	0	0
m	j	0	$-al$	0	cj

[243]. The defining equations of this case are

$$0 = ik = il = im,$$

which give

$$0 = jk = jl = jm.$$

* Substitute for m, $ai + m$, and the algebra separates. [C. S. P.]

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There are two cases:

[2431], when $ki = l,\ li = m,\ mi = 0$;
[2432], when $ki = l,\ li = mi = 0$.

[2431]. The defining equations of this case are

$$ki = l, \quad li = m, \quad mi = 0,$$

which give

$$\begin{aligned}
&kj = m, \quad lj = mj = 0 = lk = mk = l^2 = lm = ml = m^2,\\
&0 = ik^2 = ikl = ikm = a_3 = a_{34} = a_{35},\\
&k^2i = kl = c_3l + d_3m,\\
&kli = km = c_3m, \quad 0 = k^3m = c_3 = km,\\
&0 = k^3 = b_3m + d_3^2m = b_3 + d_3^2.
\end{aligned}$$

There are two cases:

[2431^1], when c_3 does not vanish;
[24312], when c_3 vanishes.

[2431^1]. The defining equation of this case can be reduced to

$$c_3 = 1.$$

This gives a quintuple algebra which may be called (bp_5), its multiplication table being *

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* The structure of this algebra may be exhibited by putting $k_1 = i + a^{-1}j - a^{-1}k$, $l_1 = j - a^{-1}l$, $m_1 = -a^{-1}m$, when the multiplication table becomes

	i	j	k	l	m
i	j	0	j	0	0
j	0	0	0	0	0
k	l	m	0	0	0
l	m	0	m	0	0
m	0	0	0	0	0

In relative form, $i = B:C + C:D$, $j = B:D$, $k = A:B + C:D$, $l = A:C$, $m = A:D$. [C. S. P.]

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(bp_5)	i	j	k	l	m
i	j	0	0		0
j	0	0	0	0	0
k	l	m	$-a^2j+al+m$	am	0
l	m	0	0	0	0
m	0	0	0	0	0

[24312]. The defining equation of this case is

$$e_3 = 0.$$

This gives a quintuple algebra which may be called (bq_5), its multiplication table being*

(bq_5)	i	j	k	l	m
i	j	0	0	0	0
j	0	0	0	0	0
k	l	m	$-a^2j+al$	am	0
l	m	0	0	0	0
m	0	0	0	0	0

[2432]. The defining equations of this case are

$$ki = l, \quad li = mi = 0,$$

* On substituting $k_1 = i - a^{-1}k$, $l_1 = j - a^{-1}l$, $m_1 = a^{-1}m$, this algebra reduces to (bp_5), in the form given in the last note. [C. S. P.]

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which give

$$0 = kj = lj = mj = lk = l^2 = lm = ik^2 = a_2,$$
$$kl = c_3 l, \quad 0 = k^2 l = c_2 = kl,$$
$$0 = ikm = a_{35} = kmi = c_{35} = k^2 m = e_{35} = imk = a_{33},$$
$$ml = c_{53} l, \quad 0 = m^2 l = c_{53} = ml = mk^2 = e_{53};$$

and it may be assumed that

$$k^2 = m,$$

which gives

$$0 = k^3 = km = mk = m^2.$$

There is then a quintuple algebra which may be called (br_5), its multiplication being *

(br_5)	i	j	k	l	m
i	j	0	0	0	0
j	0	0	0	0	0
k	l	0	m	0	0
l	0	0	0	0	0
m	0	0	0	0	0

[25]. The defining equations of this case are

$$0 = i^3 = j^3 = k^3 = l^2 = m^2 = ij + ji = ik + ki = il + li = im + mi,$$
$$0 = jk + kj = jl + lj = jm + mj = kl + lk = km + mk = lm + ml;$$

and it may be assumed that

$$ij = k = -ji, \quad il = m = -li;$$

* In relative form, $i = D:E + E:F$. $j = D:F$. $k = A:B + B:F + C:E$. $l = C:F$. $m = A:F$. [C. S. P.]

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which gives

$$0 = ik = ki = jk = kj = im = mi = km = mk = lm = ml,$$
$$ijk = kl = b_{24}k + d_{24}m = -ilj = -mj = jm,$$
$$0 = j^2m = d_{24}jm = d_{24} = kl^2 = b_{24}kl = b_{24} = kl = lk = jm = mj,$$
$$0 = j^2l = a_{24}k = a_{24},$$
$$i(c_{24}j + e_{24}l) = c_{24}k + e_{24}m,$$
$$j(c_{24}j + e_{24}k) = e_{24}(c_{24}k + e_{24}m),$$
$$l(c_{24}j + e_{24}l) = -e_{24}(c_{24}k + e_{24}m);$$

so that it is easy to see that there is no pure algebra in this case.

SEXTUPLE ALGEBRA.

There are two cases:

[1], when there is an idempotent basis;
[2], when the algebra is nilpotent.

[1]. The defining equation of this case is

$$i^2 = i.$$

There are 19 cases:

[1^5], when all the other units but i are in the first group;
[12], when j, k, l, m are in the first and n in the second group;
[13], when j, k and l are in the first and m and n in the second group;
[14], when j, k and l are in the first, m in the second and n in the third group;
[15], when j and k are in the first and l, m and n in the second group;
[16], when j and k are in the first, l and m in the second and n in the third group;
[17], when j and k are in the first, l in the second, m in the third, and n in the fourth group;
[18], when j is in the first, and k, l, m and n in the second group;
[19], when j is in the first, k, l and m in the second, and n in the third group;
[10′], when j is in the first, k and l in the second, and m and n in the third group;
[11′], when j is in the first, k and l in the second, m in the third and n in the fourth group;
[12′], when j is in the first, k in the second, l in the third and m and n in the fourth group;

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[13′], when j, k, l, m and n are in the second group;
[14′], when j, k, l and m are in the second and m in the third group;
[15′], when j, k and l are in the second and m and n are in the third group;
[16′], when j, k and l are in the second, m in the third, and n in the fourth group;
[17′], when j and k are in the second, l and m in the third, and n in the fourth group;
[18′], when j and k are in the second, l in the third, and m and n in the fourth group;
[19′], when j is in the second, k in the third, and l, m and n in the fourth group.

[1⁴]; The defining equations of this case are

$$ij = ji = j, \quad ik = ki = k, \quad il = li = l, \quad im = mi = m, \quad in = ni = n,$$

and the 54 algebras of this case deduced from (q_5) to (br_5) may be called (a_6) to (bb_6).*

[12]. The defining equations of this case are

$$ij = ji = j, \quad ik = ki = k, \quad il = li = l, \quad im = mi = m, \quad in = n, \quad ni = 0,$$

which give

$$0 = jn = nj = kn = nk = ln = nl = mn = nm = n^2,$$

so that there is no pure algebra in this case.

[13]. The defining equations of this case are

$$ij = ji = j, \quad ik = ki = k, \quad il = li = l, \quad im = m, \quad in = n, \quad mi = ni = 0.$$

There are four cases, which correspond to relations between the units of the first group similar to those of the quadruple algebras (a_4), (b_4), (c_4) or (d_4).

[131]. The defining equations of this case are

$$j^2 = k, \quad jk = kj = l, \quad jl = k^2 = kl = lj = lk = l^2 = 0;$$

and, in the result, we obtain

$$jm = n, \quad jn = km = kn = lm = ln = 0.$$

* The multiplication tables of these algebras, formed from the nilpotent quintuple algebras, in the same manner in which the first class of quintuple algebras are formed from the nilpotent quadruple algebras, have been omitted. [C. S. P.]

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This gives a sextuple algebra which may be called (bc_6), of which the multiplication table is *

(bc_6)	i	j	k	l	m	n
i	i	j	k	l	m	n
j	j	k	l	0	n	0
k	k	l	0	0	0	0
l	l	0	0	0	0	0
m	0	0	0	0	0	0
n	0	0	0	0	0	0

[132]. The defining equations of this case are

$$j^2 = k = l^2, \quad lj = ak, \quad jk = jl = kj = k^2 = kl = lk = 0,$$

which give

$$km = kn = 0.$$

There are two cases:

[1321], when e_{24} does not vanish;

[132^1], when e_{24} vanishes.

[1321]. The defining equation of this case can be reduced to

$$jn = m,$$

which gives

$$0 = jm = lm.$$

This gives a sextuple algebra which may be called (lal_6), of which the multiplication table is †

* In relative form, $i = A:A + B:B + C:C + D:D$, $j = A:B + B:C + C:D$, $k = A:C + B:D$, $l = A:D$, $m = B:E$, $n = A:E$. [C. S. P.]

† This algebra is distinguishable into two, in the same manner as (e_3). Namely, if $a = \pm 2$, on substituting $l_1 = l \pm j$, we have $l^2 = 0$, $jl = k$, $lj = -k$, and the multiplication table is otherwise unchanged. Otherwise, on substituting $j_1 = l + cj$, $l_1 = k + c^{-1}j$, where $2c = -a \pm \sqrt{a^2 - 4}$, we have $j^2 = l^2 = 0$, $jl = (1 - c^2)k$, $lj = (1 - c^{-2})k$, $jn = (b + c)k$, $ln = (b + c^{-1})k$, and otherwise the multiplication table is unchanged. The following is a relative form for the first variety: $i = A:A + B:B + C:C + D:D$, $j = A:B + B:D + C:D$, $k = A:D$, $l = A:C - B:D$, $m = A:E$, $n = B:E + bC:E$. For the second variety, $i = A:A + B:B + C:C + D:D$, $j = A:B + (1 - c^2)C:D$, $k = A:D$, $l = A:C + (1 - c^{-2})B:D$, $m = A:E$, $n = (b + c)B:E + (b + c^{-1})C:E$. [C. S. P.]

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(bd_6)	i	j	k	l	m	n
i	i	j	k	l	m	n
j	j	k	0	0	0	m
k	k	0	0	0	0	0
l	l	ak	0	k	0	bm
m	0	0	0	0	0	0
n	0	0	0	0	0	0

[132^3]. The defining equation of this case is

$$jn = 0,$$

and there is no pure algebra in this case.

[13^3]. The defining equations of this case are

$$j^2 = k, \quad lj = k, \quad jk = jl = kj = k^2 = kl = lk = l^2 = 0,$$

which give

$$km = kn = 0.$$

There is a sextuple algebra in this case which may be called (be_6), of which the multiplication table is *

* This algebra may be a little simplified by substituting $j - l$ for j. In relative form, $i = A:A + B:B + C:C + D:D$, $j = A:D + B:C$, $k = A:C$, $l = A:B$, $m = A:E$, $n = bB:E + aD:E$. [C. S. P.]

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(be_6)	i	j	k	l	m	n
i	i	j	k	l	m	n
j	j	k	0	0	0	am
k	k	0	0	0	0	0
l	l	k	0	0	0	bm
m	0	0	0	0	0	0
n	0	0	0	0	0	0

[134]. The defining equations of this case are

$$jk = -kj = l, \quad j^2 = k^2 = jk = kj = kl = lk = l^2 = 0.$$

There is a sextuple algebra in this case which may be called (bf_6), of which the multiplication table is *

(bf_6)	i	j	k	l	m	n
i	i	j	k	l	m	n
j	j	0	0	k	0	m
k	k	0	0	0	0	0
l	l	$-k$	0	0	0	am
m	0	0	0	0	0	0
n	0	0	0	0	0	0

* In relative form, $i = A:A+B:B+C:C+D:D$, $j = A:B-C:D$, $k = A:D$, $l = A:C+B:D$, $m = A:E$, $n = B:E+aC:E$. [C. S. P.]

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[14]. The defining equations of this case are

$$ij = ji = j, \quad ik = ki = k, \quad il = li = l, \quad im = m, \quad ni = n, \quad mi = in = 0,$$

which give

$$0 = jm = jn = km = kn = lm = ln = mj = nj = mk = nk = ml = nl = m^2 = nm = n^2.$$

There are four cases defined as in [13].

[141]. The defining equations of this case are

$$j^2 = k, \quad jk = kj = l, \quad jl = k^2 = kl = lj = lk = l^2 = 0,$$

which give

$$mn = d_{56} l.$$

There is a sextuple algebra which may be called (bg_6), of which the multiplication table is*

(bg_6)	i	j	k	l	m	n
i	i	j	k	l	m	0
j	j	k	l	0	0	0
k	k	l	0	0	0	0
l	l	0	0	0	0	0
m	0	0	0	0	0	l
n	n	0	0	0	0	0

[142]. The defining equations of this case are the same as in [132], which give

$$mn = c_{56} k.$$

* In relative form, $i = A:A+B:B+C:C+D:D$, $j = A:B+B:C+C:D$, $k = A:C+B:D$, $l = A:D$, $m = A:E$, $n = E:D$. [C. S. P.]

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There is a sextuple algebra which may be called (bh_6), of which the multiplication table is *

(bh_6)	i	j	k	l	m	n
i	i	j	k	l	m	0
j	j	k	0	0	0	0
k	k	0	0	0	0	0
l	l	ak	0	k	0	0
m	0	0	0	0	0	k
n	n	0	0	0	0	0

[143]. The defining equations of this case are the same as in [13²]. There is a sextuple algebra which may be called (bi_6), of which the multiplication table is †

(bi_6)	i	j	k	l	m	n
i	i	j	k	l	m	0
j	j	k	0	0	0	0
k	k	0	0	0	0	0
l	l	k	0	0	0	0
m	0	0	0	0	0	k
n	n	0	0	0	0	0

* This algebra has two varieties, analogous to those of (c_1). The first is, in relative form, $i = A : A + B : B + C : C + D : D$, $j = A : B + B : C + A : D$, $k = A : C$, $l = -A : B + D : C$, $m = A : E$, $n = E : C$. The second in relative form is the same except that $j = A : B + b^{-1}D : C$, $l = A : D - bB : C$. [C. S. P.]

† This algebra may be slightly simplified by putting $j - l$ for j. Then, in relative form, $i = A : A + B : B + C : C$, $j = B : C$, $k = A : C$, $l = A : B$, $m = A : D$, $n = D : C$. [C. S. P.]

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[14²]. The defining equations of this case are the same as in [134]. There is a sextuple algebra which may be called (bj_6), of which the multiplication table is *

(bj_6)	i	j	k	l	m	n
i	i	j	k	l	m	0
j	j	0	0	k	0	0
k	k	0	0	0	0	0
l	l	$-k$	0	0	0	0
m	0	0	0	0	0	k
n	n	0	0	0	0	0

[15]. The defining equations of this case are

$$ij = ji = j, \quad ik = ki = k, \quad il = l, \quad im = m, \quad in = n, \quad li = mi = ni = 0,$$

which give

$$j^2 = k, \quad 0 = jk = kj = k^2 = lj = lk = l^2 = lm = ln = mj = mk = ml = m^2 = mn = nj = nk = nl = nm = n^2.$$

There is a sextuple algebra which may be called (bk_6), of which the multiplication table is †

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* $i = A:A + B:B + C:C + D:D$, $j = A:B - C:D$, $k = A:D$, $l = A:C + B:D$, $m = A:E$, $n = E:D$. [C. S. P.]

† In relative form, $i = A:A + B:B + C:C$, $j = A:B + B:C$, $k = A:C$, $l = C:D$, $m = B:D$, $n = A:D$. [C. S. P.]

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(bk_6)	i	j	k	l	m	n
i	i	j	k	l	m	n
j	j	k	0	m	n	0
k	k	0	0	n	0	0
l	0	0	0	0	0	0
m	0	0	0	0	0	0
n	0	0	0	0	0	0

[16]. The defining equations of this case are

$$ij = ji = j, \quad ik = ki = k, \quad il = l, \quad im = m, \quad ni = n, \quad li = mi = in = 0,$$

which give

$$j^2 = k, \quad 0 = jk = jn = kj = k^2 = kn = lj = lk = l^2 = lm = mj = mk = nl = m^2 = nj = nk = nl = nm = n^2.$$

There is a sextuple algebra which may be called (bl_6), of which the multiplication table is *

(bl_6)	i	j	k	l	m	n
i	i	j	k	l	m	0
j	j	k	0	m	0	0
k	k	0	0	0	0	0
l	0	0	0	0	0	k
m	0	0	0	0	0	0
n	n	0	0	0	0	0

* In relative form, $i = A:A + B:B + C:C$, $j = A:B + B:C$, $k = A:C$, $l = B:D + A:E$, $m = A:D$, $n = E:C$. [C. S. P.]

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[17]. The defining equations of this case are

$$ij = ji = j, \quad ik = ki = k, \quad il = l, \quad mi = m, \quad li = im = in = ni = 0.$$

There is no pure algebra in this case.

[18]. The defining equations of this case are

$$ij = ji = j, \quad ik = k, \quad il = l, \quad im = m, \quad in = n, \quad ki = li = mi = ni = 0.$$

There is no pure algebra in this case.

[19]. The defining equations of this case are

$$ij = ji = j, \quad ik = k, \quad il = l, \quad im = m, \quad ni = n, \quad in = kl = li = ni = n.$$

There is no pure algebra in this case.

[10′]. The defining equations of this case are

$$ij = ji = j, \quad ik = k, \quad il = l, \quad mi = m, \quad ni = n, \quad im = in = ki = li = 0.$$

There is no pure algebra in this case.

[11′]. The defining equations of this case are

$$ij = ji = j, \quad ik = k, \quad il = l, \quad mi = m, \quad im = li = in = ni = 0.$$

There is no pure algebra in this case.

[12′]. The defining equations of this case are

$$ij = ji = j, \quad ik = k, \quad li = l, \quad il = im = in = ki = mi = ni = 0.$$

There is no pure algebra in this case.

[13′]. The defining equations of this case are

$$ij = j, \quad ik = k, \quad il = l, \quad im = m, \quad in = n, \quad ji = ki = li = mi = ni = 0.$$

There is no pure algebra in this case.

[14′]. The defining equations of this case are

$$ij = j, \quad ik = k, \quad il = l, \quad im = m, \quad ni = n, \quad ji = ki = li = mi = in = 0.$$

There is no pure algebra in this case.

[15′]. The defining equations of this case are

$$ij = j, \quad ik = k, \quad il = l, \quad mi = m, \quad ni = n, \quad im = in = ji = ki = li = 0.$$

There is no pure algebra in this case.

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[16′]. The defining equations of this case are

$$ij = j, \quad ik = k, \quad il = l, \quad mi = m, \quad im = in = jk = kl = li = ni = 0.$$

There is no pure algebra in this case.

[17′]. The defining equations of this case are

$$ij = j, \quad ik = k, \quad li = l, \quad mi = m, \quad il = im = in = ji = ki = ni = 0.$$

There is no pure algebra in this case.

[18′]. The defining equations of this case are

$$ij = j, \quad ik = k, \quad li = l, \quad ji = ki = il = im = in = mi = ni = 0.$$

There are six cases:

[18′1], when $m^2 = m$, $mn = n$, $nm = 0$,
[18′2], when $m^2 = m$, $mn = 0$, $nm = n$,
[18′3], when $m^2 = n$, $mn = nm = 0$, $n^2 = m$,
[18′4], when $m^2 = m$, $mn = nm = n^2 = 0$,
[18′5], when $m^2 = n$, $m^3 = 0$,
[18′6], when $m^2 = n^2 = 0$.

[18′1]. The defining equations of this case are

$$m^2 = m, \quad mn = n, \quad nm = 0.$$

There are two cases:

[18′1²], when $ml = 0$;
[18′12], when $ml = l$.

[18′1²]. The defining equation of this case is

$$ml = 0.$$

There is no pure algebra in this case.

[18′12]. The defining equation of this case is

$$ml = l.$$

There are two cases:

[18′121], when $jm = j$;
[18′12²], when $jm = 0$.

[18′121]. The defining equation of this case is

$$jm = j.$$

There is a sextuple algebra which may be called (bm_6), of which the multiplication table is *

* In relative form, $i = A:A$, $j = A:B$, $k = A:C$, $l = B:A$, $m = B:B$, $n = B:C$. [C. S. P.]

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(bm_s)	i	j	k	l	m	n
i	i	j	k	0	0	0
j	0	0	0	i	j	k
k	0	0	0	0	0	0
l	l	m	n	0	0	0
m	0	0	0	l	m	n
n	0	0	0	0	0	0

[18′12²]. The defining equation of this case is

$$jm = 0.$$

There is no pure algebra in this case.

[18′2]. The defining equations of this case are

$$m^2 = m, \quad mn = 0, \quad nm = n.$$

There are two cases:

[18′21], when $ml = l$;
[18′2²], when $ml = 0$.

[18′21]. The defining equation of this case is

$$ml = l.$$

There are two cases:

[18′21²], when $jm = j$;
[18′212], when $jm = 0$.

[18′21²]. The defining equation of this case is

$$jm = j.$$

There is no pure algebra in this case.

[18′212]. The defining equation of this case is

$$jm = 0.$$

There is no pure algebra in this case.

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[18′2²]. The defining equation of this case is

$$ml = 0.$$

There is no pure algebra in this case.

[18′3]. The defining equations of this case are

$$m^2 = m, \quad mn = nm = 0, \quad n^2 = n.$$

There is no pure algebra in this case.

[18′4]. The defining equations of this case are

$$m^2 = m, \quad mn = nm = n^2 = 0.$$

There are two cases:

[18′41], when $jm = j$;
[18′42], when $jm = 0$.

[18′41]. The defining equation of this case is

$$jm = j.$$

There is no pure algebra in this case.

[18′42]. The defining equation of this case is

$$jm = 0.$$

There is no pure algebra in this case.

[18′5]. The defining equations of this case are

$$m^2 = n, \quad m^3 = 0.$$

There is no pure algebra in this case.

[18′6]. The defining equations of this case are

$$m^2 = n^2 = 0.$$

There is no pure algebra in this case.

[19′]. The defining equations of this case are

$$ij = j, \quad ki = k, \quad ji = ik = il = im = in = li = mi = ni = 0.$$

There is no pure algebra in this case.

[2]. The algebras belonging to this case are not investigated, because it is evident from § 69 that they are rarely of use unless combined with an idempotent basis, so as to give septuple algebras.

NATURAL CLASSIFICATION.

There are many cases of these algebras which may obviously be combined into natural classes, but the consideration of this portion of the subject will be reserved to subsequent researches.

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ADDENDA.

I.

On the Uses and Transformations of Linear Algebra.

BY BENJAMIN PEIRCE.

[*Presented to the American Academy of Arts and Sciences, May* 11, 1875.]

Some definite interpretation of a linear algebra would, at first sight, appear indispensable to its successful application. But on the contrary, it is a singular fact, and one quite consonant with the principles of sound logic, that its first and general use is mostly to be expected from its want of significance. The interpretation is a trammel to the use. Symbols are essential to comprehensive argument. The familiar proposition that all A is B, and all B is C, and therefore all A is C, is contracted in its domain by the substitution of significant words for the symbolic letters. The A, B, and C, are subject to no limitation for the purposes and validity of the proposition; they may represent not merely the actual, but also the ideal, the impossible as well as the possible. In Algebra, likewise, the letters are symbols which, passed through a machinery of argument in accordance with given laws, are developed into symbolic results under the name of formulas. When the formulas admit of intelligible interpretation, they are accessions to knowledge; but independently of their interpretation they are invaluable as symbolical expressions of thought. But the most noted instance is the symbol called the impossible or imaginary, known also as the square root of minus one, and which, from a shadow of meaning attached to it, may be more definitely distinguished as the symbol of *semi-inversion*. This symbol is restricted to a precise signification as the representative of perpendicularity in quaternions, and this wonderful algebra of space is intimately dependent upon the special use of the symbol for its symmetry, elegance, and power. The immortal author of quaternions has shown that there are other significations which may attach to the symbol in other cases. But the strongest use of the symbol is to be found in its magical power of doubling the actual universe, and

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placing by its side an ideal universe, its exact counterpart, with which it can be compared and contrasted, and, by means of curiously connecting fibres, form with it an organic whole, from which modern analysis has developed her surpassing geometry. The letters or units of the linear algebras, or to use the better term proposed by Mr. Charles S. Peirce, the *vids* of these algebras, are fitted to perform a similar function each in its peculiar way. This is their primitive and perhaps will always be their principal use. It does not exclude the possibility of some special modes of interpretation, but, on the contrary, a higher philosophy, which believes in the capacity of the material universe for all expressions of human thought, will find, in the utility of the vids, an indication of their probable reality of interpretation. Doctor Hermann Hankel's alternate numbers, with Professor Clifford's applications to determinants, are a curious and interesting example of the possible advantage to be obtained from the new algebras. Doctor Spottiswoode in his fine, generous, and complete analysis of my own treatise before the London Mathematical Society in November of 1872, has regarded these numbers as quite different from the algebras discussed in my treatise, because they are neither linear nor limited. But there is no difficulty in reducing them to a linear form, and, indeed, my algebra (e_3) is the simplest case of Hankel's alternate numbers; and in any other case, in which n is the number of the Hankel elements employed, the complete number of vids of the corresponding linear algebra is $2^n - 1$. The limited character of the algebras which I have investigated may be regarded as an accident of the mode of discussion. There is, however, a large number of unlimited algebras suggested by the investigations, and Hankel's numbers themselves would have been a natural generalization from the proposition of § 65 of my algebra.* Another class of unlimited algebras, which would readily occur from the inspection of those which are given, is that in which all the powers of a vid are adopted as independent vids, and the highest power may either be zero, or unity, or the vid itself, and the zero power of the fundamental vid, *i. e.* unity itself, may also be retained as a vid. But I desire to draw especial attention to that class, which is also unlimited, and for which, when it was laid before the mathematical society of London in January of 1870, Professor Clifford proposed the appropriate name of *quadrates*.

* This remark is not intended as a foundation for a claim upon the Hankel numbers, which were published in 1867, three years prior to the publication of my own treatise.—B. P. [They were given much earlier under the name of *clefs* by Cauchy, and (substantially) at a still earlier date by Grassmann. —C. S. P.]

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Quadrates.

The best definition of quadrates is that proposed by Mr. Charles S. Peirce. If the letters A, B, C, etc., represent absolute quantities, differing in quality, the vids may represent the relations of these quantities, and may be written in the form

$$(A:A)\,(A:B)\,(A:C)\ \ldots\ (B:A)\,(B:B)\ \ldots\ (C:A),\ \text{etc.}$$

subject to the equations

$$(A:B)\,(B:C) = (A:C)$$
$$(A:B)\,(C:D) = 0.$$

In other words, every product vanishes, in which the second letter of the multiplier differs from the first letter of the multiplicand; and when these two letters are identical, both are omitted, and the product is the vid which is compounded of the remaining letters, which retain their relative position.

Mr. Peirce has shown by a simple logical argument that the quadrate is the legitimate form of a complete linear algebra, and that all the forms of the algebras given by me must be imperfect quadrates, and has confirmed this conclusion by actual investigation and reduction. His investigations do not however dispense with the analysis by which the independent forms have been deduced in my treatise, though they seem to throw much light upon their probable use.

Unity.

The sum of the vids $(A:A)$, $(B:B)$, $(C:C)$, etc., extended so as to include all the letters which represent absolute quantities in a given algebra, whether it be a complete or an incomplete quadrate, has the peculiar character of being idempotent, and of leaving any factor unchanged with which it is combined as multiplier or multiplicand. This is the distinguishing property of unity, so that this combination of the vids can be regarded as unity, and may be introduced as such and called the *vid of unity*. There is no other combination which possesses this property.

But any one of the vids $(A:A)$, $(B:B)$, etc., or the sum of any of these vids is idempotent. There are many other idempotent combinations, such as

$$(A:A) + x\,(A:B),\quad y\,(A:B) + (B:B),$$
$$\tfrac{1}{2}\,(A:A) + \tfrac{1}{2}\,(A:B) + \tfrac{1}{2}\,(B:A) + \tfrac{1}{2}\,(B:B),$$

which may deserve consideration in making transformations of an algebra preparatory to its application.

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Inversion.

A vid which differs from unity, but of which the square is equal to unity, may be called a *vid of inversion.* For such a vid when applied to some other combination transforms it; but, whatever the transformation, a repetition of the application restores the combination to its primitive form. A very general form of a vid of inversion is

$$(A:A) \pm (B:B) \pm (C:C) \pm \text{etc.},$$

in which each doubtful sign corresponds to two cases, except that at least one of the signs must be negative. The negative of unity might also be regarded as a symbol of inversion, but cannot take the place of an independent vid. Besides the above vids of inversion, others may be formed by adding to either of them a vid consisting of two different letters, which correspond to two of the one-lettered vids of different signs; and this additional vid may have any numerical coefficient whatever. Thus

$$(A:A) + (B:B) - (C:C) + x(A:C) + y(B:C)$$

is a vid of inversion.

The new vid which Professor Clifford has introduced into his biquaternions is a vid of inversion.

Semi-Inversion.

A vid of which the square is a vid of inversion, is a *vid of semi-inversion.* A very general form of a vid of semi-inversion is

$$(A:A) \pm (B:B) \pm \jmath(C:C) \pm \text{etc.}$$

in which one or more of the terms $(A:A)$, $(B:B)$, etc., have $\jmath$ for a coefficient. The combination

$$(A:A) \pm \jmath(B:B) + x(A:B) + \text{etc.}$$

is also a vid of semi-inversion. With the exception of unity, all the vids of Hamilton's quaternions are vids of semi-inversion.

The Use of Commutative Algebras.

Commutative algebras are especially applicable to the integration of differential equations of the first degree with constant coefficients. If i, j, k,

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etc., are the vids of such an algebra, while x, y, z, etc., are independent variables, it is easy to show that a solution may have the form $F(xi + yj + zk + \text{etc.})$, in which F is an arbitrary function, and i, j, k, etc., are connected by some simple equation. This solution can be developed into the form

$$F(xi + yj + zk + \text{etc.}) = Mi + Nj + Pk + \text{etc.}$$

in which M, N, P, etc., will be functions of x, y, z, etc., and each of them is a solution of the given equation. Thus in the case of Laplace's equation for the potential of attracting masses, the vids must satisfy the equation

$$i^2 + j^2 + k^2 = 0.$$

The algebra (a_3) of which the multiplication table is

	i	j	k
i	i	j	k
j	j	k	0
k	k	0	0

may be used for this case. Combinations i_1, j_1, k_1 of these vids can be found which satisfy the equation

$$i_1^2 + j_1^2 + k_1^2 = 0,$$

and if the functional solution

$$F(xi_1 + yj_1 + zk_1)$$

is developed into the form of the original vids

$$Mi + Nj + Pk,$$

M, N, and P will be independent solutions, of such a kind that the surfaces for which N and P are constant will be perpendicular to that for which M is constant, which is of great importance in the problems of electricity.

The Use of Mixed Algebras.

It is quite important to know the various kinds of pure algebra in making a selection for special use, but mixed algebras can also be used with advantage

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in certain cases. Thus, in Professor Clifford's biquaternions, of which he has demonstrated the great value, other vids can be substituted for unity and his new vid, namely their half sum and half difference, and each of the original vids of the quaternions can be multiplied by these, giving us two sets of vids, each of which will constitute an independent quadruple algebra of the same form with quaternions. Thus if i, j, k, are the primitive quaternion vids and w the new vid, let

$$\begin{aligned} \alpha_1 &= \tfrac{1}{2}(1+w). & \alpha_2 &= \tfrac{1}{2}(1-w). \\ i_1 &= \alpha_1 i. & i_2 &= \alpha_2 i. \\ j_1 &= \alpha_1 j. & j_2 &= \alpha_2 j. \\ k_1 &= \alpha_1 k. & k_2 &= \alpha_2 k. \end{aligned}$$

Then since

$$\begin{aligned} \alpha_1^2 &= \alpha_1. & \alpha_2^2 &= \alpha_2. \\ i_1^2 = j_1^2 = k_1^2 &= -\alpha_1. & i_2^2 = j_2^2 = k_2^2 &= -\alpha_1. \\ i_1 j_1 &= k_1 = -j_1 i_1. & i_2 j_2 &= k_2 = -j_2 i_2. \\ j_1 k_1 &= i_1 = -k_1 j_1. & j_2 k_2 &= i_2 = -k_2 j_2. \\ k_1 i_1 &= j_1 = -i_1 k_1. & k_2 i_2 &= j_2 = -i_2 k_2. \end{aligned}$$

$$\alpha_1 \alpha_2 = 0 = \alpha_2 \alpha_1.$$

$$M_1 N_2 = 0 = N_2 M_1.$$

in which M_1 denotes any combination of the vids of the first algebra, and N_2 any combination of those of the second algebra. It may perhaps be claimed that these algebras are not independent, because the sum of the vids α_1 and α_2 is absolute unity. This, however, should be regarded as a fact of interpretation which is not apparent in the defining equations of the algebras.

II.

On the Relative Forms of the Algebras.

BY C. S. PEIRCE.

Given an associative algebra whose letters are i, j, k, l, etc., and whose multiplication table is

$$\begin{aligned} i^2 &= a_{11} i + b_{11} j + c_{11} k + \text{etc.}^* \\ ij &= a_{12} i + b_{12} j + c_{12} k + \text{etc.} \\ ji &= a_{21} i + b_{21} j + c_{21} k + \text{etc.}, \\ &\text{etc., etc.} \end{aligned}$$

I proceed to explain what I call the relative form of this algebra.

* I have used a_{11}, etc., in place of the a_1, etc., used by my father in his text.

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Let us assume a number of new units, A, I, J, K, L, etc., one more in number than the letters of the algebra, and every one except the first, A, corresponding to a particular letter of the algebra. These new units are susceptible of being multiplied by numerical coefficients and of being added together;* but they cannot be multiplied together, and hence are called *non-relative* units.

Next, let us assume a number of operations each denoted by bracketing together two non-relative units separated by a colon. These operations, equal in number to the square of the number of non-relative units, may be arranged as follows:

$$\begin{array}{llll} (A:A) & (A:I) & (A:J) & (A:K), \text{ etc.} \\ (I:A) & (I:I) & (I:J) & (I:K), \text{ etc.} \\ (J:A) & (J:I) & (J:J) & (J:K), \text{ etc.} \end{array}$$

Any one of these operations performed upon a polynomial in non-relative units, of which one term is a numerical multiple of the letter following the colon, gives the same multiple of the letter preceding the colon. Thus, $(I:J)(aI+bJ+cK)=bI$.† These operations are also taken to be susceptible of associative combination. Hence $(I:J)(J:K)=(I:K)$; for $(J:K)K=J$ and $(I:J)J=I$, so that $(I:J)(J:K)K=I$. And $(I:J)(K:L)=0$; for $(K:L)L=K$ and $(I:J)K=(I:J)(0.J+K)=0.I=0$. We further assume the application of the distributive principle to these operations; so that, for example,

$$\{(I:J)+(K:J)+(K:L)\}(aJ+bL)=aJ+(a+b)K.$$

Finally, let us assume a number of complex operations denoted by i', j', k', l', etc., corresponding to the letters of the algebra and determined by its multiplication table in the following manner:

$$\begin{aligned} i' &= (I:A)+a_{11}(I:I)+b_{11}(J:I)+c_{11}(K:I)+\text{etc.} \\ &\quad +a_{12}(I:J)+b_{12}(J:J)+c_{12}(K:J)+\text{etc.} \\ &\quad +a_{13}(I:K)+b_{13}(J:K)+c_{13}(K:K)+\text{etc.}+\text{etc.} \\ j' &= (J:A)+a_{21}(I:I)+b_{21}(J:I)+c_{21}(K:I)+\text{etc.} \\ &\quad +a_{22}(I:J)+b_{22}(J:J)+c_{22}(K:J)+\text{etc.} \\ &\quad +a_{23}(I:K)+b_{23}(J:K)+c_{23}(K:K)+\text{etc.}+\text{etc.} \\ k' &= \text{etc.} \end{aligned}$$

* Any one of them multiplied by 0 gives 0. † If $b=0$, of course the result is 0.

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Any two operations are equal which, being performed on the same operand, invariably give the same result. The ultimate operands in this case are the non-relative units. But any operations compounded by addition or multiplication of the operations i', j', k', etc., if they give the same result when performed upon A, will give the same result when performed upon any one of the non-relative units. For suppose $i'j'A = k'l'A$. We have

$$i'j'A = i'J = a_{12}I + b_{12}J + c_{12}K + \text{etc.}$$
$$k'l'A = k'L = a_{34}I + b_{34}J + c_{34}K + \text{etc.}$$

so that $a_{12} = a_{34}$, $b_{12} = b_{34}$, $c_{12} = c_{34}$, etc., and in our original algebra $ij = kl$. Hence, multiplying both sides of the equation into any letter, say m, $ijm = klm$. But

$$ijm = i(a_{25}i + b_{25}j + c_{25}k + \text{etc.}) = (a_{11}a_{25} + a_{12}b_{25} + a_{13}c_{25} + \text{etc.})i + (b_{11}a_{25} + b_{12}b_{25} + b_{13}c_{25} + \text{etc.})j + \text{etc.}$$

But we have equally

$$i'j'm'A = (a_{11}a_{25} + a_{12}b_{25} + a_{13}c_{25} + \text{etc.})I + (b_{11}a_{25} + b_{12}b_{25} + b_{13}c_{25} + \text{etc.})J + \text{etc.}$$

So that $i'j'm'A = k'l'm'A$. Hence, $i'j'M = k'l'M$. It follows, then, that if $i'j'A = k'l'A$, then $i'j'$ into any non-relative unit equals $k'l'$ into the same unit, so that $i'j' = k'l'$. We thus see that whatever equality subsists between compounds of the accented letters i', j', k', etc., subsists between the same compounds of the corresponding unaccented letters i, j, k, so that the multiplication tables of the two algebras are the same.* Thus, what has been proved is that any associative algebra can be put into relative form, *i. e.* (see my *brochure* entitled *A brief Description of the Algebra of Relatives*) that every such algebra may be represented by a matrix.

Take, for example, the algebra (bd_5). It takes the relative form

$$i = (I:A) + (J:I) + (L:K), \quad j = (J:A),$$
$$k = (K:A) + (J:I) + \mathfrak{r}(L:I) + (I:K) + (M:K) + \mathfrak{r}(J:L) - (J:M) - \mathfrak{r}(L:M),$$
$$l = (L:A) + (J:K), \quad m = (M:A) + (\mathfrak{r}^2 - 1)(J:I) - (L:K) - \mathfrak{r}^2(J:M).$$

* A brief proof of this theorem, perhaps essentially the same as the above, was published by me in the *Proceedings of the American Academy of Arts and Sciences*, for May 11, 1875.

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This is the same as to say that the general expression $xi + yj + zk + ul + vm$ of this algebra has the same laws of multiplication as the matrix

$$\begin{array}{cccccc}
0, & 0, & 0, & 0, & 0, & 0, \\
x, & 0, & 0, & z, & 0, & 0, \\
y, & \begin{matrix} x+z \\ +(\mathfrak{r}^2-1)v, \end{matrix} & 0, & u, & \mathfrak{r}z, & -z-\mathfrak{r}^2 v, \\
z, & 0, & 0, & 0. & 0, & 0, \\
u, & \mathfrak{r}z, & 0, & x-v, & 0, & -\mathfrak{r}z \\
v, & 0, & 0, & z, & 0, & 0.
\end{array}$$

Of course, every algebra may be put into relative form in an infinity of ways; and simpler ways than that which the rule affords can often be found. Thus, for the above algebra, the form given in the foot-note is simpler, and so is the following:

$$i = (B:A) + (C:B) + (F:D) + (C:E), \quad j = (C:A),$$
$$k = (D:A) + (E:D) + (C:B) + \mathfrak{r}(F:B) + \mathfrak{r}(C:F),$$
$$l = (F:A) + (C:D), \quad m = (E:A) + (\mathfrak{r}^2-1)(C:B) - (B:A) - (F:D) - (C:E).$$

These different forms will suggest transformations of the algebra. Thus, the relative form in the foot-note to (bd_5) suggests putting

$$i_1 = i + m, \quad j_1 = \mathfrak{r}^2 j, \quad k_1 = k + \mathfrak{r}^{-1} i + \mathfrak{r}^{-1} m, \quad l_1 = \mathfrak{r} l + j, \quad m_1 = -m,$$

when we get the following multiplication table, where ρ is put for $\mathfrak{r}^{-1}$:

	i	j	k	l	m
i	0	0	0	0	j
j	0	0	0	0	0
k	0	0	i	j	l
l	0	0	ρj	0	0
m	$\rho^2 j$	0	ρl	0	j

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Ordinary algebra with imaginaries, considered as a double algebra, is, in relative form,

$$1 = (X:X) + (Y:Y), \quad \jmath = (X:Y) - (Y:X).$$

This shows how the operation $\jmath$ turns a vector through a right angle in the plane of X, Y. Quaternions in relative form is

$$\begin{aligned} 1 &= (W:W) + (X:X) + (Y:Y) + (Z:Z), \\ i &= (X:W) - (W:X) + (Z:Y) - (Y:Z), \\ j &= (Y:W) - (Z:X) - (W:Y) + (X:Z), \\ k &= (Z:W) + (Y:X) - (X:Y) - (W:Z). \end{aligned}$$

We see that we have here a reference to a space of four dimensions corresponding to X, Y, Z, W.

III.

On the Algebras in which Division is Unambiguous.

By C. S. PEIRCE.

1. In the *Linear Associative Algebra*, the coefficients are permitted to be imaginary. In this note they are restricted to being real. It is assumed that we have to deal with an algebra such that from $AB = AC$ we can infer that $A = 0$ or $B = C$. It is required to find what forms such an algebra may take.

2. If $AB = 0$, then either $A = 0$ or $B = 0$. For if not, $AC = A(B + C)$, although A does not vanish and C is unequal to $B + C$.

3. The reasoning of § 40 holds, although the coefficients are restricted to being real. It is true, then, that since there is no expression (in the algebra under consideration) whose square vanishes, there must be an expression, i, such that $i^2 = i$.

4. By § 41, it appears that for every expression in the algebra we have

$$iA = Ai = A.$$

5. By the reasoning of §53, it appears that for every expression A there is an equation of the form

$$\Sigma_m (a_m A^m) + bi = 0.$$

But i is virtually arithmetical unity, since $iA = Ai = A$; and this equation may be treated by the ordinary theory of equations. Suppose it has a real root, α; then it will be divisible by $(A - \alpha)$, and calling the quotient B we shall have

$$(A - \alpha i) B = 0.$$

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But $A - \alpha i$ is not zero, for A was supposed dissimilar to i. Hence a product of finites vanishes, which is impossible. Hence the equation cannot have a real root. But the whole equation can be resolved into quadratic factors, and some one of these must vanish. Let the irresoluble vanishing factor be

$$(A - s)^2 + t^2 = 0.$$

Then

$$\left(\frac{A - s}{t}\right)^2 = -1,$$

or, every expression, upon subtraction of a real number (*i. e.* a real multiple of i), can be converted, in one way only, into a quantity whose square is a negative number. We may express this by saying that every quantity consists of a scalar and a vector part. A quantity whose square is a negative number we here call a *vector*.

6. Our next step is to show that the vector part of the product of two vectors is linearly independent of these vectors and of unity. That is, i and j being any two vectors,* if

$$ij = s + v$$

where s is a scalar and v a vector, we cannot determine three real scalars a, b, c, such that

$$v = a + bi + cj.$$

This is proved, if we prove that no scalar subtracted from ij leaves a remainder $bi + cj$. If this be true when i and j are any unit vectors whatever, it is true when these are multiplied by real scalars, and so is true of every pair of vectors. We will, then, suppose i and j to be unit vectors. Now,

$$ij^2 = -i.$$

If therefore we had

$$ij = a + bi + cj,$$

we should have

$$-i = ij^2 = aj + bij - c = ab - c + b^2 i + (a + bc)j;$$

whence, i and j being dissimilar,

$$-i = b^2 i, \qquad b^2 = -1,$$

and b could not be real.

* The idempotent basis having been shown to be arithmetical unity, we are free to use the letter i to denote another unit.

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7. Our next step is to show that, i and j being any two vectors, and

$$ij = s + v,$$

s being a scalar and v a vector, we have

$$ji = r(s - v),$$

where r is a real scalar. It will be obviously sufficient to prove this for the case in which i and j are unit vectors. Assuming them such, let us write

$$ji = s' + v', \qquad vv' = s'' + v'',$$

where s' and s'' are scalars, while v' and v'' are vectors. Then

$$ij.ji = (s + v)(s' + v') = ss' + sv' + s'v + v'' + s''.$$

But we have

$$ij.ji = ij^2 i = -i^2 = 1.$$

Hence,

$$v'' = 1 - ss' - s'' - sv' - s'v.$$

But v'' is the vector of vv', so that by the last paragraph such an equation cannot subsist unless v'' vanishes. Thus we get

$$0 = 1 - ss' - s'' - sv' - s'v,$$

or

$$sv' = 1 - ss' - s'' - s'v.$$

But a quantity can only be separated in one way into a scalar and a vector part; so that

$$sv' = -s'v.$$

That is,

$$ji = \frac{s'}{s}(s - v). \quad Q.E.D.$$

8. Our next step is to prove that $s = s'$; so that if $ij = s + v$ then $ji = s - v$. It is obviously sufficient to prove this when i and j are unit vectors. Now from any quantity a scalar may be subtracted so as to leave a remainder whose square is a scalar. We do not yet know whether the sum of two vectors is a vector or not (though we do know that it is not a scalar). Let us then take such a sum as $ai + bj$ and suppose x to be the scalar which subtracted from it makes the square of the remainder a scalar. Then, C being a scalar,

$$(-x + ai + bj)^2 = C.$$

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But developing the square we have

$$(-x+ai+bj)^2 = x^2 - a^2 - b^2 + abs + abs' - 2axi + 2bxj + ab\left(1-\frac{s'}{s}\right)v = C;$$

i. e.

$$ab\left(1-\frac{s'}{s}\right)v = C - x^2 + a^2 + b^2 - abs - abs' + 2axi + 2bxj.$$

But v being the vector of ij, by the last paragraph but one the equation must vanish. Either then $v=0$ or $1-\frac{s'}{s}=0$. But if $v=0$, $ij=s$, and multiplying into j,

$$-i = sj,$$

which is absurd, i and j being dissimilar. Hence $1-\frac{s'}{s}=0$ and

$$ji = s - v. \quad Q.E.D.$$

9. The number of independent vectors in the algebra cannot be two. For the vector of ij is independent of i and j. There may be no vector, and in that case we have the ordinary algebra of reals; or there may be only one vector, and in that case we have the ordinary algebra of imaginaries.

Let i and j be two independent vectors such that

$$ij = s + v.$$

Let us substitute for j

$$j_1 = si + j.$$

Then we have

$$\begin{aligned} ij_1 &= v, \quad j_1 i = -v, \\ j_1 v &= j_1 ij_1 = -j_1^2 i = i, \quad vj_1 = ij_1^2 = -i, \\ iv &= i^2 j_1 = -j_1, \quad vi = ij_1 i = -j_1 i^2 = j_1. \end{aligned}$$

Thus we have the algebra of real *quaternions*. Suppose we have a fourth unit vector, k, linearly independent of all the others, and let us write

$$\begin{aligned} j_1 k &= s' + v', \\ ki &= s'' + v''. \end{aligned}$$

Let us substitute for k

$$k_1 = s''i + s'j_1 + k,$$

and we get

$$\begin{aligned} j_1 k_1 &= -s''v + v', \quad k_1 j_1 = s''v - v', \\ k_1 i &= -s'v + v'', \quad ik_1 = s'v - v''. \end{aligned}$$

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Let us further suppose

$$(ij_1)\,k_1 = s'' + v'''.$$

Then, because ij_1 is a vector,

$$k_1\,(ij_1) = s''' - v'''.$$

But

$$k_1 j_1 = -\,j_1 k_1\,, \quad k_1 i = -\,ik_1\,,$$

because both products are vectors.

Hence

$$i\,.\,j_1 k_1 = -\,i\,.\,k_1 j_1 = -\,ik_1\,.\,j_1 = k_1 i\,.\,j_1 = k_1\,.\,ij_1\,.$$

Hence

$$s''' + v''' = s''' - v'''$$

or $v''' = 0$, and the product of the two unit vectors is a scalar. These vectors cannot, then, be independent, or k cannot be independent of $ij = v$. Thus it is proved that a fourth independent vector is impossible, and that ordinary real algebra, ordinary algebra with imaginaries, and real quaternions are the only associative algebras in which division by finites always yields an unambiguous quotient.

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On Tchebycheff's Theory of the Totality of the Prime Numbers comprised within given Limits.

By J. J. Sylvester.

If it be admitted that Legendre's approximate formula for the number of prime numbers inferior to a given number, which has been confirmed by direct enumeration of the number of prime numbers contained in the first few millions, can be extended to those remote regions of number which transcend the limits and even the possibilities of human experience, it will follow as a consequence that the average density of the distribution of prime numbers in the neighborhood of a large quantity x approximates to $\frac{1}{\log x}$, and consequently that the number of primes included between x and $(1+\varepsilon)x$, or if we like to say so, between $x+A$ and $(1+\varepsilon)x+B$, will be approximately equal to $\frac{\varepsilon x}{\log x}$, and therefore will become indefinitely great, however small ε may be taken. Although there can hardly be a doubt that such is the fact, no step had been taken previous to Tchebycheff's researches towards establishing this proposition demonstratively. Tchebycheff has succeeded in proving it, not, it is true, in an absolute sense, but for all values of ε exceeding the fraction $\frac{1}{5}$. He has done more, inasmuch as he has given formulae for actually ascertaining a number x for all values superior to which there will be at least any specified number K of primes included between $x+A$ and $(1+\varepsilon)x+B$ when ε has any positive value superior to $\frac{1}{5}$, and A and B are any quantities positive or negative. He may not perhaps have actually stated this proposition in so many words, but it is an immediate inference

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from the limits (expressed in terms of x, $x^{\frac{1}{2}}$ and $\log x$) which he has obtained to the number of prime numbers not exceeding x. The object of what follows is to make a little further advance in the same direction, and to show upon Tchebycheff's own principles that the proposition remains true when ϵ is conditioned no longer to be inferior to the fraction $\frac{1}{5}$, but to the fraction $\frac{1}{6} + \frac{1}{4642_{11}^{10}}$, so that the excess above unity (the region so to say of darkness) is scarcely more than five-sixths of what it is for the first named fraction. This conclusion is arrived at by aid exclusively of Tchebycheff's own formulae.

Tchebycheff's method may be regarded as the *first* approximation to the inferior and superior limits of a quantity ψx subject to the conditions

$$Vx > Ax + F \log x,$$

$$Vx < Ax + F_1 \log x,$$

where $Vx = \psi x - \psi \frac{x}{6} + \psi \frac{x}{7} - \psi \frac{x}{10}$ etc. (see Serret's *Cours d'Algèbre supérieure*, 4th Ed., Vol. 2, pp. 230–233), and to the further conditions that ψx is not less than $\psi x'$ if $x > x'$, and that $\psi x = 0$ when $x < 1$.

The limits obtained for ψx depend exclusively on these definitions, and would be applicable to any function ψx whatever that satisfied them.

The advance made in this article consists in pursuing the approximation through an indefinite number of steps, so as to bring the superior and inferior limits to ψx continually nearer and nearer to each other as regards the *principal* term (a multiple of x) which enters into each of them: the remaining terms over and above this multiple of x in the expressions for the limits always continue to be positive integer powers of $\log x$, and consequently the ratio of the limits becomes as nearly as we please identical with the ratio of the principal terms (*i. e.* of their coefficients) when x is taken sufficiently great: this ratio as given in the first approximation is $\frac{6}{5}$, but as the approximation is continued continually converges to but never reaches the fraction $\frac{7}{6} + \frac{1}{4642_{11}^{10}}$.

Such, and such only, is the small but not unimportant contribution here supplied to Tchebycheff's remarkable theory. As no allusion is made to the possibility of this contraction of the limits in a work published so recently as 1879, by an

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author so competent as M. Serret, I presume that it has hitherto remained unnoticed; but of this I cannot speak with certainty, inasmuch as it was enough for M. Serret's purpose to obtain for the ratio of the principal terms a number less than 2; that being sufficient for the object he had in view, which was to prove M. Bertrand's celebrated postulate that at least one prime number must be included $\left(\text{for all values of } x \text{ greater than } \frac{7}{2}\right)$ between x and $2x-2$.

Although I might confine myself exclusively to the determination of the limits to ψx which flow from the conditions above given, it is, I think, desirable to supply a brief summary of M. Tchebycheff's method, so as to point out the connexion between the determination of these limits and the limits to "the totality of the prime numbers comprised within a given range." In so doing I shall adopt for the convenience of reference the notation which I find in M. Serret's able exposition of the subject (*Alg. sup.*, Vol. 2, pp. 225–239).

θx stands for the sum of the logarithms of all the *prime* numbers not exceeding x.

$$\psi x = \theta x + \theta x^{\frac{1}{2}} + \theta x^{\frac{1}{3}} + \theta x^{\frac{1}{4}} + \theta x^{\frac{1}{5}} + \quad \ldots .$$

$$Tx = \psi x + \psi \frac{x}{2} + \psi \frac{x}{3} + \psi \frac{x}{4} + \psi \frac{x}{5} + \ldots$$

and, as a consequence founded on purely arithmetical considerations, Tx is the sum of the logarithms of *all* the numbers not exceeding x, and therefore, as an easy deduction from Stirling's theorem, it follows that for all values of x superior to unity,

$$Tx < x \log x - x + \frac{1}{2} \log x + \left(\log \sqrt{2\pi} + \frac{1}{12}\right)$$

$$Tx > x \log x - x - \frac{1}{2} \log x + \log \sqrt{2\pi}.$$

If then Vx (a notation not in Serret) be used to denote

$$Tx - T\frac{x}{2} - T\frac{x}{3} - T\frac{x}{5} + T\frac{x}{30}$$

$\left(\text{where it should be noticed that } 1 - \frac{1}{2} - \frac{1}{3} - \frac{1}{5} + \frac{1}{30} = 0\right)$, limits for Vx can be found in which $x \log x$ will not appear, and expressed solely in terms of x and $\log x$: it may in fact be shown that for all values of x superior to unity,

$$Vx > A(x-1) - \frac{5}{2} \log x$$

$$Vx < A(x-1) + \frac{5}{2} \log x$$

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where $A = \frac{1}{2}\log 2 + \frac{1}{3}\log 3 + \frac{1}{5}\log 5 - \frac{1}{30}\log 30 = .92129202\ldots$

The limits actually employed, however, are the slightly wider ones,

$$Vx > Ax - \frac{5}{2}\log x - 1$$

$$Vx < Ax + \frac{5}{2}\log x.$$

If now we take an infinite succession of numbers separable into batches of sixteen, such that every $(i+1)^{\text{th}}$ batch may be got by adding $30i$ to each of the numbers in the first batch, those numbers being

1, 6, 7, 10, 11, 12, 13, 15, 17, 18, 19, 20, 23, 24, 29, 30

(where it is perhaps worth noticing that leaving out the last number 30, the remaining 15 consist of a middle term 15 and pairs of numbers whose sum is always 30, disposed symmetrically about that middle term), it will readily be seen to follow from the expression for V in terms of the T's and of T in terms of the ψ's, that

$$\left.\begin{aligned} Vx = \psi x &- \psi\tfrac{x}{6} + \psi\tfrac{x}{7} - \psi\tfrac{x}{10} + \psi\tfrac{x}{11} - \psi\tfrac{x}{12} + \psi\tfrac{x}{13} - \psi\tfrac{x}{15} \\ &+ \psi\tfrac{x}{17} - \psi\tfrac{x}{18} + \psi\tfrac{x}{19} - \psi\tfrac{x}{20} + \psi\tfrac{x}{23} - \psi\tfrac{x}{24} + \psi\tfrac{x}{29} - \psi\tfrac{x}{30} \end{aligned}\right\}$$
$$\left.\begin{aligned} &+ \psi\tfrac{x}{31} - \psi\tfrac{x}{36} \quad \ldots\ldots\ldots\

From the limits to which Vx is subject (Vx being now regarded as representing the series of ψ's above written) limits can be found to ψx of the form $mx + R_1(\log x)$, $nx + R_2(\log x)$, where the R's signify rational integer forms of function. In the first approximation, for the inferior and superior limits respectively, $m = A$, $n = 6\frac{A}{5}$; R_1 is a linear and R_2 a quadratic form of function. In the approximation of the i^{th} order m and n will become functions of i, and R_1, R_2 will be of the i^{th} and $(i+1)^{\text{th}}$ orders respectively in $\log x$.

The limits of ψx being supposed to be given (say $\psi' x$ the superior and $\psi_1 x$ the inferior limit), $\psi' x$ will serve as a superior and $\psi_1 x - 2\psi' x^{\frac{1}{2}}$ as an inferior limit to θx. But instead of $\psi' x$ we may use (although not at all necessary for the object in view) the slightly closer limit $\psi' x - \psi_1 x^{\frac{1}{2}}$, which is what M. Serret employs, and equally instead of $\psi_1 x - 2\psi' x^{\frac{1}{2}}$ we might use the slightly closer limit

$$\psi_1 x - \psi' x^{\frac{1}{2}} - \psi' x^{\frac{1}{3}} - \psi' x^{\frac{1}{4}} + \psi_1 x^{\frac{1}{6}},$$

which, probably as leading to calculations needlessly complicated (as regards the object in view), M. Serret does not employ. In any case, following the same notation as before to distinguish the two limits, we shall obtain

$$\theta' x = nx + F(x^{\frac{1}{2}}, \log x)$$

$$\theta_1 x = mx + F'(\ \ldots\ , \log x),$$

where F, F' are rational integer forms of function, and the dots in the F' may be filled in either with $x^{\frac{1}{2}}$ or with $x^{\frac{1}{2}}$, $x^{\frac{1}{3}}$, $x^{\frac{1}{4}}$, $x^{\frac{1}{6}}$; and we shall have

$$\theta' x = nx(1 + \varepsilon_x) \qquad \theta_1 x = mx(1 + \eta_x),$$

where ε_x and η_x vanish when $x = \infty$.

To come to our ultimate object, it is obvious that the number of primes between x and $(1+\rho)x$ will be greater than $[\theta_1(1+\rho)x - \theta' x] \div \log x$. It will therefore be greater than $\frac{[m(1+\rho) - n]x + \delta_x}{\log x}$, where $\delta_x = 0$ when $x = \infty$. Hence we may find a value of x so great that the number of primes shall be at least K by finding a number x sufficiently large to make $\theta_1(1+\rho)x - \theta' x - (K-1)\log x > 0$, which it must always be possible to do provided that $m(1+\rho) > n$, *i. e.* that $\rho > \left(\frac{n}{m} - 1\right)$. Hence the importance of diminishing

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what I call the asymptotic ratio $\frac{n}{m}$, *i. e.* the ratio of the coefficients in the principal terms of the superior and inferior limit to ψx. That is what I shall now proceed to accomplish, but first it is necessary to establish a certain easy lemma.

Suppose the equation $fx - f\frac{x}{c} = Ax^m$ is to be satisfied; this can be done by writing $fx = A\frac{c^m}{c^m - 1}x$, and in particular if $m = 1$, the only case that the present theory demands, $fx = \frac{c}{c-1}Ax$. Again if the equation $fx - f\frac{x}{c} = P(\log x)^\mu$ is to be satisfied, this may be done by making $fx = P_0(\log x)^{\mu+1} + P_1(\log x)^\mu + P_2(\log x)^{\mu-1} + \ldots + P_\mu \log x$, for since $\log\frac{x}{c} = (\log x - \log c)$, $fx - f\frac{x}{c}$ will then obviously become a function of $\log x$ of the μ^{th} order, which may be identified with $P(\log x)^\mu$ by properly assigning the values of the $(\mu + 1)$ disposable constants $P_0, P_1, P_2, \ldots P_\mu$. In fact the equation might easily (if it were worth while to do so) be turned into an equation of differences, and the general values of the P's be expressed once for all in terms of Bernoulli's numbers for any value of μ. Hence it follows that the equation

$$fx - f\frac{x}{c} = Nx + R_\mu^* \log x,$$

where R_μ is a rational integer form of function of the μ^{th} order, may be satisfied by making

$$fx = \frac{c}{c-1}Nx + R_{\mu+1}\log x,$$

where the second term on the right hand side of the equation is a *known* function of $\log x$ of the $(\mu + 1)^{\text{th}}$ order.

Suppose now that the inequality $\psi x - \psi\frac{x}{c} < Nx + R_\mu \log x$, where $c > 1$, is given, and it is desired to extract from this inequality an inferior limit to ψx. It is only necessary to get a solution of the equation $fx - f\frac{x}{c} = Nx + R_\mu \log x$.

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* The reader's attention is called to the fact that R_μ is used throughout to denote a *form of function*, and not, like P_μ, a *coefficient*.

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We shall then have

$$\downarrow x - \downarrow \frac{x}{c} < fx - f\frac{x}{c}$$

$$\downarrow \frac{x}{c} - \downarrow \frac{x}{c^2} < f\frac{x}{c} - f\frac{x}{c^2}$$

$$\downarrow \frac{x}{c^2} - \downarrow \frac{x}{c^3} < f\frac{x}{c^2} - f\frac{x}{c^3}$$

$$\cdot \quad \cdot \quad \cdot \quad \cdot \quad \cdot \quad \cdot \quad \cdot \quad \cdot$$

$$\cdot \quad \cdot \quad \cdot \quad \cdot \quad \cdot \quad \cdot \quad \cdot \quad \cdot$$

$$\cdot$$

and consequently $$fx - f\frac{x}{c^q} > \downarrow x - \downarrow \frac{x}{c^q}.$$

If then q be supposed to be taken such that $\frac{x}{c^q}$, say z, lies between 0 and 1, we shall have

$$fx - \downarrow x > fz,$$

and *à fortiori* $> R_{\mu+1} \log z$ (if N be positive, as is the case throughout the present investigation), where the right hand side of the inequality is a known rational integer function of $\log z$. If then M be a number less than the least value that $R_{\mu+1}\xi$ can assume between the limits $\xi = 0$, $\xi = -\log c$, we shall have $\downarrow x < fx - M$, and an inferior limit will have been obtained to $\downarrow x$.

In the first approximation (Serret, p. 234), where $\mu = 1$ and $c = 6$, $R_2\xi = \frac{5}{4 \log 6}\xi^2 + \frac{5}{4}\xi$, the minimum value of which is got by taking $2\xi = -\log 6$ or $\xi = -\log \sqrt{6}$ (which happens to lie between the limits of $\log 1$ and $-\log 6$) and gives $M = \frac{-5 \log 6}{16}$, so that $\downarrow x < fx + \frac{5 \log 6}{16}$. The actual value employed for the superior limit, as sufficiently near and more convenient for use, is $fx + 1$.

So in the general case we shall have $fx - \downarrow x > M$ where M is any number less than the least value of $R_{\mu+1}\xi$ for values of ξ lying between 0 and $-\log c$. It may or may not be the absolute minimum of $R_{\mu+1}\xi$ that has to be taken according as the value of ξ which gives this absolute minimum does or does not lie between 0 and $-\log c$. In the latter case it may be either some other minimum, or one of the values of $R_{\mu+1}\xi$ corresponding to the extreme values $\xi = 0$ and $\xi = -\log c$, which might be found by trial. But a method practically better and sufficient for the demands made by the present investigation,

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would be to substitute zero in place of any term in the function of ξ of the form $+K\xi^{2m}$ or $-K\xi^{2m+1}$, and for any term of the form $-K\xi^{2m}$ or $+K\xi^{2m+1}$ to substitute $-K(\log c)^{2m}$ and $-K(\log c)^{2m+1}$ respectively.

For instance, in the case just considered we might have written $M = -\frac{5}{4}\log 6$, and the superior limit instead of being $fx+1$ would have been $fx+\frac{5}{4}\log 6$, which would practically have been just as good. With a view to a remark which will subsequently be made it is well to notice that the inequality

$$\psi x - \psi\frac{x}{c} > Nx + R, \log x$$

may also be solved precisely in the same manner, and will give for an inferior limit to ψx (using fx to signify the very same function as before) $fx - M_1$, where (N being supposed positive) $M_1 = -N\log c +$ any quantity not less than the greatest value of a known rational integer function of a variable conditioned to lie between 0 and $-\log c$, which may either be found by an exact algebraical process or by substituting 0 in those two cases where previously $-\log c$, and $-\log c$ in those other two cases where previously 0 was to be substituted for the variable.

The lemma needful for our purposes may now accordingly be stated in the following terms: *If $\psi x - \psi\frac{x}{c}$ is less or greater than Nx + a given rational integer function of $\log x$ of any given order*, ψx is less or greater than $\frac{c}{c-1}Nx$ + a known (and easily determinable) rational integer function of $\log x$ of the order next superior.

If the coefficients of x in the superior and inferior limit to ψx at any stage of the investigation be called u and v; I shall show that these values will serve to give (step by step) other superior and inferior limits where u and v are replaced by quantities u', v', such that $u' < u$, $v' > v$; u', v' being known linear functions of u, v. We shall thus be led to a system of two simultaneous linear equations of differences in order to obtain the effect of those changes repeated any number, finite or infinite, of times: but for greater clearness I shall begin with supposing that one of the two expressions u, v, viz. v (which undergoes far less modification than the other) is kept constant. There will then result a single scheme of successive substitutions leading to the construction of a single linear equation in differences.

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The first step will then be as follows:

$$\psi x - \psi\tfrac{x}{6} < Ax + \tfrac{5}{2}\log x - \psi\tfrac{x}{7} + \psi\tfrac{x}{10}$$

$$< Ax + \tfrac{5}{2}\log x - \left(A\tfrac{x}{7} - \tfrac{5}{2}\log\tfrac{x}{7} - 1\right) + \tfrac{6}{50}Ax + \tfrac{5}{4\log 6}\left(\log\tfrac{x}{10}\right)^2 + \tfrac{5}{4}\log\tfrac{x}{10}$$

or writing

$$\lambda = \log 6,\ \mu = \log 7,\ \nu = \log 10,$$

$$\psi x - \psi\tfrac{x}{6} < \tfrac{171}{175}Ax + \tfrac{5}{4\lambda}(\log x)^2 + \left(\left(\tfrac{25}{4} - \tfrac{5\nu}{2\lambda}\right)\log x + \tfrac{5\nu^2}{4\lambda} - \tfrac{5}{2}\mu - \tfrac{5}{4}\nu + 1\right).$$

Hence $$\psi x < \tfrac{1026}{875}Ax + P(\log x)^3 + Q(\log x)^2 + Rx - M,$$

where first to find P, Q, R, we have the three equations

$$3P\lambda = \tfrac{5}{4\lambda}$$

$$-3P\lambda^2 + 2Q\lambda = \tfrac{25}{4} - \tfrac{5\nu}{2\lambda}$$

$$P\lambda^3 - Q\lambda^2 + R\lambda = \tfrac{5\nu^2}{4\lambda} - \tfrac{5}{2}\mu - \tfrac{5}{4}\nu + 1$$

i. e. $$P = \tfrac{5}{12\lambda^3};\quad Q = \tfrac{15}{4\lambda} - \tfrac{5\nu}{4\lambda^3};\quad R = -\tfrac{5}{12} + \tfrac{15}{4} - \tfrac{5\nu}{2\lambda} + \tfrac{5\nu^2}{4\lambda^2} - \tfrac{5\mu}{2\lambda} + \tfrac{1}{\lambda}.$$

Here P is positive; Q, whose sign depends on that of $3 - \frac{\log 10}{\log 6}$, is also positive;

and $$R = \tfrac{10}{3} + 5\left(\tfrac{\nu}{2\lambda} - \tfrac{1}{2}\right)^2 - \tfrac{5\mu - 2}{2\lambda} - \tfrac{5}{4}$$

$$= 3.33333\ldots + .10160\ldots - 2.1570\ldots - 1.25$$
$$= 3.43493\ldots - 3.4070\ldots, \text{ which is also positive.}$$

Hence we may make

$$M = -P\lambda^3 - R\lambda,$$

or $$-M = 1 + \tfrac{15}{4}\lambda - \tfrac{5(\mu+\nu)}{2} + \tfrac{5\nu^2}{4\lambda} = 1.2947.$$

It is quite possible, and even most likely, that the minimum of $P\lambda^3 - Q\lambda^2 + R\lambda$ (within the prescribed limits) would be found to exceed -1 were it worth while to go through the arithmetical calculations necessary to obtain it, but it is

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quite sufficiently near for all practical purposes to use the value above determined, or even to take $-M$ as great as 2 and to adopt for our new superior limit $\frac{171}{175}Ax + P(\log x)^3 + Q(\log x)^2 + R\log x + 2$.

In like manner this new limit will enable us to find another, and it is obvious that the general form of the limit obtained after i of these steps have been gone through will be $u_i Ax + R_{i+2}\log x$, where

$$u_i = \frac{6}{5}\left(1 - \frac{1}{7} + \frac{u_{i-1}}{10}\right) \qquad i.\,e. \quad u_i - \frac{3\,u_{i-1}}{25} = \frac{36}{35}.$$

Putting

$$u_i = \omega_i + h$$

and making

$$\frac{22}{25}h = \frac{36}{35}, \qquad i.\,e. \qquad h = \frac{90}{77},$$

we have

$$\omega_i - \frac{3}{25}\omega_{i-1} = 0.$$

Hence

$$u_i = C\left(\frac{3}{25}\right)^i + \frac{90}{77}.$$

The ultimate value of u_i is therefore $\frac{90}{77}$, and accordingly, by repeating the process indicated a sufficient number of times, we shall have for a superior limit $\left(\frac{90}{77} - \varepsilon_i\right)Ax + R_{i+2}\log x$, where ε_i may be made as small as we please by taking i sufficiently great, and thus the ultimate asymptotic ratio of the two limits is $\frac{90}{77}$ instead of $\frac{6}{5}$.

Another mode of approximation may be used, as shown in what follows.

Since

$$\psi x - \psi\tfrac{x}{10} < Ax - \psi\tfrac{x}{6} + \psi\tfrac{x}{7};$$

if we have found

$$\psi x < u_i' Ax + R_{i+2}\log x$$

we shall have

$$\psi x - \psi\tfrac{x}{10} < Ax + u_i' A\tfrac{x}{6} - A\tfrac{x}{7} + R_{i+2}'\log x,$$

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and therefore

$$\psi x < u'_{i+1} Ax + R_{i+2} \log x,$$

where

$$u'_{i+1} = \frac{10}{9}\left\{1 - \frac{1}{7} + \frac{1}{6}\, u'_i\right\}$$

i. e.

$$u'_{i+1} - \frac{5}{27}\, u'_i = \frac{20}{21};$$

or

$$u'_i = K\left(\frac{5}{27}\right)^i + h'$$

where

$$h' = \frac{27}{22} \cdot \frac{20}{21} = \frac{90}{77}.$$

Thus $h' = h$ and consequently also, if we suppose each of the two sorts of approximation to start from the same point, $K = C$.

Hence the ultimate value of u_i and u'_i is the same, but the former method of approximation is to be preferred, as the same number of steps, *i. e.* the same value of i, makes $C\left(\frac{5}{27}\right)^i + h$ always $> C\left(\frac{3}{25}\right)^i + h$. The corresponding values of u_i, u'_i have the same initial and final values, but for every intermediate value of i, $u_i < u'_i$. In fact u_i, u'_i are ordinates to the same abscissa of two non-intersecting curves, having a common starting point and a common asymptote.

The maximum value of $u'_i - u_i$ is found by making $\left(\frac{5}{27}\right)^i - \left(\frac{3}{25}\right)^i$ a maximum, which takes place when i is the integer next above or next below the value

$$\frac{\log\log\frac{25}{3} - \log\log\frac{27}{5}}{\log\frac{25}{3} - \log\frac{27}{5}},$$ which is obviously less than unity.

Hence after the *first* approximation u_i and u'_i are always drawing closer together.

We may now proceed to the more (but only very slightly more) advantageous method of approximation, viz. that in which the principal terms in both limits are simultaneously varied, decreasing as before in the superior, and now at the same time increasing in the inferior limit.

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Suppose then that we have found

$$\psi x < u_i\, Ax + R_{i+2} \log x$$
$$\psi x > v_i\, Ax + R_{i+1} \log x;$$

observing that $\frac{v_i}{24} - \frac{u_i}{29}$ is always positive, we shall succeed in increasing the principal term of the inferior limit by writing $\psi x > Ax + v_i A\frac{x}{24} - u_i A\frac{x}{29}$ $+ R_{i+2} \log x$, and slightly more than previously diminishing the principal term in the superior limit by writing $\psi x - \psi\frac{x}{6} < Ax - v_i A\frac{x}{7} + u_i A\frac{x}{10} + R'_{i+2} \log x$. We shall thus easily derive

$$\psi x > v_{i+1}\, Ax + R_{i+2} \log x$$
$$\psi x < u_{i+1}\, Ax + R_{i+2} \log x$$

where

$$v_{i+1} = 1 + \frac{v_i}{24} - \frac{u_i}{29}$$

$$u_{i+1} = \frac{6}{5}\left(1 - \frac{v_i}{7} + \frac{u_i}{10}\right) = \frac{6}{5} - \frac{6}{35} v_i + \frac{3}{25} u_i$$

or, making $v_i = v'_i + f$, $u_i = u'_i + e$,

$$v'_{i+1} - \frac{1}{24} v'_i + \frac{1}{29} u'_i = 0$$

$$u'_{i+1} - \frac{3}{25} u'_i + \frac{6}{35} v'_i = 0,$$

if $\frac{23}{24} f + \frac{1}{29} e = 1$, $\frac{6}{35} f + \frac{22}{25} e = \frac{6}{5}$.

So that calling ρ_1, ρ_2 the roots of $\begin{vmatrix} \rho - \frac{1}{24} & ; & \frac{1}{29} \\ \frac{6}{35} & ; & \rho - \frac{3}{25} \end{vmatrix} = 0$

$$u_i = C_1 \rho_1^i + C_2 \rho_2^i + e$$
$$v_i = C'_1 \rho_1^i + C'_2 \rho_2^i + f.$$

The equation for finding ρ_1, ρ_2 is

$$\rho^2 - \frac{97}{600}\rho - \frac{37}{40600} = 0$$

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whence

$$\rho_1 = .167253\ldots \qquad \rho_2 = .005637\ldots$$

Also the equations in e, f give e, f (the values of u_∞, r_∞) as follows:

$$e = \frac{59595}{50999} \qquad f = \frac{51072}{50999}$$

If there were any use in obtaining the values of the disposable constants they could of course be obtained from the equations

$$C_1 + C_2 + e = u_0 = \frac{6}{5} \qquad C_1\rho_1 + C_2\rho_2 + e = u_1 = \frac{1026}{875}$$

$$C_1' + C_2' + f = r_0 = 1 \qquad C_1'\rho_1 + C_2'\rho_2 + f = r_1 = \frac{3481}{3480}$$

The asymptotic ratio of the two limits is

$$\frac{e}{f} = \frac{59595}{51072} = \frac{6}{7} + \frac{11}{51072}$$

Various other modes of approximation may be adopted, but it will be found that no smaller value can be obtained for the asymptotic ratio than that above given: the value of u_∞ cannot be made less than $\frac{59595}{50999}$, nor the value of r_∞ greater than $\frac{51072}{50999}$.

Thus *ex. gr.* making use of the inequality

$$\psi x - \psi_6^x > Ax - \psi_7^x + \psi_{24}^x - \psi_{29}^x + R(\log x),$$

we might by the lemma obtain

$$\psi x > \frac{6}{5} A\left(1 - \frac{u_i}{7} - \frac{u_i}{29} + \frac{r_i}{24}\right) + R_{i+3}\log x,$$

and consequently

$$r_{i+1} = \frac{6}{5}\left(1 - \frac{u_i}{7} - \frac{u_i}{29} + \frac{r_i}{24}\right);$$

combining which with the previous equation for u_{i+1} we should have for finding u_∞, r_∞ say e', f' the two equations,

$$\frac{19}{24}f' + \frac{36}{203}e' = 1$$

$$\frac{6}{35}f' + \frac{22}{25}e' = \frac{6}{5}$$

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and consequently

$$e' = \frac{331905}{284029} \qquad f' = \frac{284424}{284069}.$$

Reduced to decimals

$$e = 1.16855\ldots \quad f = 1.00143\ldots$$
$$e' = 1.16856\ldots \quad f' = 1.00125\ldots$$

It may be noticed that $eA = 1.006774\ldots$, $fA = .992619\ldots$ of which the sum is nearly 1.999394, and their mean nearly .999697, whereas the mean of A and $\frac{6A}{5}$ (the original coefficients of x in the limits) is nearly 1.01342. Thus the new mean is more than 44 times nearer than the latter to the true asymptotic value deducible from the empirical formula.

Were it desired merely to find superior and inferior limits to ψx in the form obtained in Tchebycheff's method, it would (as already indicated) have been sufficient to have taken for Vx, $Tx - 2T\frac{x}{2}$, which would have led to the inequalities

$$\psi x > (\log 2)\, x + R_1 \log x$$
$$\psi x < 2(\log 2)\, x + R_2 \log x$$

but the asymptotic ratio being here 2, these limits could not have conducted to a proof of M. Bertrand's postulate. If, however, we were to take $Vx = Tx - T\frac{x}{2} - T\frac{x}{3} - T\frac{x}{6}$ we should obtain

$$Vx > Bx + R_1 \log x$$
$$Vx < Bx + R_1' \log x$$

where

$$B = \frac{1}{2}\log 2 + \frac{1}{3}\log 3 + \frac{1}{6}\log 6 = 1.0114043$$

and

$$Vx = \psi x + \psi\frac{x}{5} - 2\psi\frac{x}{6} + \psi\frac{x}{7} + \psi\frac{x}{11} - 2\psi\frac{x}{12} + \ldots,$$

when we should obtain

$$\psi x - \psi\frac{x}{6} < Bx + R_1' \log x$$
$$\psi x < \frac{6}{5} Bx + R_2 \log x,$$

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and again

$$\psi x + \psi_5^x > Bx + R_1 \log x$$

$$\psi x > B\left(1 - \frac{6}{25}\right)x + R_2' \log x$$

Here the asymptotic ratio of the two limits is $\frac{30}{19}$, which being less than 2, the formulae above indicated would suffice to prove M. Bertrand's postulate, and would lead to an equation somewhat simpler in form than that led to by M. Tchebycheff's process, but whose greatest root would be considerably larger than that found by the established method; so that there would be a larger number of verifications of the postulate to be made for the lower numbers: this, however, is really a matter of very trifling importance, as the needful verifications could be made even up to 100,000 if necessary, by throwing a rapid glance over a few leaves of Burckhardt's tables.

It is noticeable that the limits above found by giving Vx the form $Tx - 2T_2^x$ are the *only* limits that can be got in such case; no process of successive approximation being here possible, on account of the too close contiguity of the successive denominators in $\psi x - \psi_2^x + \psi_3^x \ldots$

Such, however, would not be the case were we to use Vx to signify $Tx - T_2^x - T_3^x - T_6^x$, and consequently

$$Vx = \psi x + \psi_5^x - 2\psi_6^x + \psi_7^x + \psi_{11}^x - 2\psi_{12}^x + \psi_{13}^x \ldots$$

The limits expressed by the inequalities

$$\psi x < u_i\ Bx + \ldots$$
$$\psi x > v_i\ Bx + \ldots$$

would lead to the narrower limits

$$\psi x < u_{i+1}\ Bx + \ldots$$
$$\psi x > v_{i+1}\ Bx + \ldots$$

where

$$u_{i+1} = \frac{6}{5}\left(1 - \frac{v_i}{7} + \frac{u_i}{12}\right)$$

$$v_{i+1} = 1 - \frac{u_i}{5} + \frac{v_i}{6} - \frac{u_i}{11}$$

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that is to say

$$u_{t+1} - \frac{u_t}{10} + \frac{6v_t}{35} - \frac{6}{5} = 0,$$

$$\frac{u_t}{5} + \frac{u_t}{11} + v_{t+1} - \frac{v_t}{6} - 1 = 0.$$

Hence, using as before e, f to indicate the ultimate value of u_t, v_t, we should have

$$21e + 4f - 28 = 0,$$
$$96e + 275f - 330 = 0.$$

and consequently

$$e = \frac{6380}{5391}, \qquad f = \frac{4242}{5391},$$

and

$$\frac{e}{f} = \frac{6380}{4242} = \frac{3}{2} + \frac{1}{249\frac{1}{7}}$$

which is the ultimate value of the asymptotic ratio, of which the initial value was $\frac{30}{19}$, that could be found by this method.

In every such kind of series as I have denoted by Vx, it is obvious that the sum of the multiples of x under the sign of $\downarrow$ in Vx is equal to the coefficient of x in either limit to Vx. Thus *ex. gr.* in Tchebycheff's series, if we take n a multiple of 30, and make $S_n = 1 + \frac{1}{2} + \frac{1}{3} + \ldots + \frac{1}{n}$, the sum of n terms of $1 - \frac{1}{6} + \frac{1}{7} - \frac{1}{10} + \frac{1}{11} \ldots$

$$= \left(1 - \frac{1}{2} - \frac{1}{3} - \frac{1}{5} + \frac{1}{30}\right) S_n + \frac{1}{2}\left(\frac{1}{\frac{1}{2}n+1} + \frac{1}{\frac{1}{2}n+2} + \ldots + \frac{1}{n}\right)$$
$$+ \frac{1}{3}\left(\frac{1}{\frac{1}{3}n+1} + \frac{1}{\frac{1}{3}n+2} + \ldots + \frac{1}{n}\right) + \frac{1}{5}\left(\frac{1}{\frac{1}{5}n+1} + \frac{1}{\frac{1}{5}n+2} + \ldots + \frac{1}{n}\right)$$
$$- \frac{1}{30}\left(\frac{1}{\frac{1}{30}n+1} + \frac{1}{\frac{1}{30}n+2} \ldots + \frac{1}{n}\right);$$

and the multiplier of S_n being always 0, it follows that the sum of an infinite number of the consecutive terms $= \frac{1}{2}\log 2 + \frac{1}{3}\log 3 + \frac{1}{5}\log 5 - \frac{1}{30}\log 30 = A$.

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It may not unreasonably be conjectured that whilst nothing more can be done with the Tchebycheffian Vx, it may be possible to find such other form of function in lieu of it, or such infinite succession of different forms of function, as may either directly or by successive approximation bring the coefficients of x in the two limits as near as we please to one another, at the expense, of course, of proportionally lengthening out the residues, or tails as they might be termed, of the two limits. Could this be done, it is easy to demonstrate that the limit thus continually approached from opposite sides must be unity, as indicated in advance by Legendre's empirical formula. For this purpose it will be sufficient to use the simplest form of Vx, viz. $Tx - 2T\frac{x}{2}$, whence we obtain

$$\psi x - \psi\tfrac{x}{2} + \psi\tfrac{x}{3} \ldots\ldots > \log 2 \,.\, x\,(1+\varepsilon_x)$$

$$\psi x - \psi\tfrac{x}{2} + \psi\tfrac{x}{3} \ldots\ldots < \log 2 \,.\, x\,(1+\eta_x)$$

ε_x, η_x being known logarithmic quantities which vanish when $x = \infty$.

For suppose it possible to prove that

$$\psi x > Q\,(1-h)\,x + Gx$$
$$\psi x < Q\,(1+h)\,x + Fx$$

where $\frac{Fx}{x}$, $\frac{Gx}{x}$ may be made as small as we please by taking x sufficiently large, (I mean by taking x greater than some certain value ξ). Then

$$(1+\varepsilon_x)\log 2 \,.\, x < \psi x - \psi\tfrac{x}{2} + \psi\tfrac{x}{3} \ldots\ldots - \psi\tfrac{x}{2m}$$
$$< Q\,(1+h)\,x\left(1 - \tfrac{1}{2} + \tfrac{1}{3} \ldots\ldots - \tfrac{1}{2m}\right)$$
$$+ Fx - F\tfrac{x}{2} + F\tfrac{x}{3} \ldots\ldots - F\tfrac{x}{2m}.$$

Let ξ be taken so great that for all values of x greater than $\frac{\xi}{2m}$, $\frac{Fx}{x}$ shall be less in absolute numerical value than $\frac{k}{2m}$, where k is an *arbitrary* positive quantity: then, if we take $x > \xi$, the sum of the absolute values of Fx, $F\frac{x}{2}$, $F\frac{x}{3}$, $\ldots\ldots$ $F\frac{x}{2m}$, is less than kx; and *à fortiori*

$$Fx - F\tfrac{x}{2} + F\tfrac{x}{3} \ldots\ldots - F\tfrac{x}{2m} < kx.$$

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Therefore

$$Q(1+h)\log 2.x > (1+\epsilon_x)\log 2.x - kx.$$

Hence, Q being greater than $\frac{1+\epsilon_x}{1+h} - \frac{k}{(1+h)\log 2}$, and ϵ_x, h, k being all three capable of becoming indefinitely small, $1 - Q$ cannot be a finite positive quantity; which amounts to saying that $1 - Q$ cannot be positive.

In precisely the same manner, dealing with the other limit to Vx and stopping in its development at the term $\psi\frac{x}{2m+1}$ (instead of stopping at the term $-\psi\frac{x}{2m}$) it may be proved that $1 - Q$ cannot be negative. Hence $1 - Q$ must be zero, *i. e.* $Q = 1$. *Q. E. D.*

We have thus determined what is the common limit to which the principal term in the superior and in the inferior limit of ψx are bound to approximate, on the supposition of the possibility of formulae being discoverable admitting of the interval between these principal terms being capable of being made as small as we please. But to pronounce with certainty upon the existence of such possibility, we shall probably have to wait until some one is born into the world as far surpassing Tchebycheff in insight and penetration as Tchebycheff has proved himself superior in these qualities to the ordinary run of mankind.

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Specimen of a Literal Table for Binary Quantics, otherwise a Partition Table.

By Professor Cayley.

The Table, commencing $1\,;\ b\,;\ c,\ b^2\,;\ d,\ bc,\ b^3\,;\ \ldots$, is in fact a Partition Table, viz. considering the letters $b, c, d, \ldots$ as denoting 1, 2, 3, . . . respectively, it is $1^0\,;\ 1\,;\ 2,\ 11\,;\ 3,\ 12,\ 111\,;\ \ldots$ a table of the partitions of the numbers 0, 1, 2, 3 . . . , expressed however in the literal form, in order to its giving the literal terms which enter into the coefficients of any covariant of a binary quantic. The table ought to have been made and published many years ago, before the calculation of the covariants of the quintic; and the present publication of it is, in some measure, an anachronism: but I in fact felt the need of it in some calculations in regard to the sextic; and I think the table may be found useful on other occasions. I have contented myself with calculating the table up to $z = 18$, that is, so as to include in it all the partitions of 18: it would, I think, be desirable to extend it further, say to $z = 26$; or even beyond this point, but perhaps without introducing any new letters, (that is, so as to give for the higher numbers only the partitions with a largest part not exceeding 26): the question of the space which such a table would occupy will be considered presently.

As to the employment of the table, observe that in applying it to the case of a quantic $(a, b, c, d)(x, y)^3$, the terms containing the letters e, f, etc., posterior to the last coefficient d of the quantic are to be disregarded; and that the terms are to be rendered homogeneous by the introduction of the proper power of the first coefficient a, rejecting any term for which the exponent of a would be negative (or what is the same thing, any term of too high a degree in

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the coefficients b, c, d); thus, for the cubicovariant, where the coefficients are of the degree 3, and of the weights 3, 4, 5, 6 respectively, from the portion of the table

d	e	f	g
bc	bd	be	bf
b^2	c^2	cd	ce
	b^2c	b^2d	d^2
	b^4	bc^2	b^2e
		b^3c	bcd
		b^5	c^3
			b^3d
			etc.

we at once copy out the terms

a^2d	abd	acd	ad^2
abc	ac^2	b^2d	bcd
b^3	b^2c	bc^2	c^3

which compose the coefficients in question.

As regards the formation of the table, this is at once effected, and the successive terms are obtained *currente calamo*, by Arbogast's rule of the last and the last but one: observing that each term is to be regarded as containing implicitly a power of a, so that operating on any term such as b^4, the operation on the last letter gives b^3c, and that on the last but one letter gives b^5. There is little risk of error except in the accidental omission of a term; but of course any one omission would occasion the omission of all the subsequent terms derivable from the omitted term, and would so be fatal: to remove this source of error, observe that for the successive numbers 0, 1, 2, 3, etc., the number of partitions should be

0	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	...
1	1	2	3	5	7	11	15	22	30	42	56	77	101	135	176	231	297	385	...

and we can thus, for each partible number successively, verify that the right number of partitions has been obtained.

But as the number of partitions becomes large, a further control is convenient, and even necessary—say we have the 176 partitions of 15, we have by the rule to derive thence the 231 partitions of 16, and it is not until the whole of this derivation is gone through, that we could by counting the number of the new terms ascertain that the right number of 231 terms has been obtained. To break up the verification, it is convenient to know that for the partitions of 16 into 1 part, 2 parts, 3 parts, 4 parts, etc., the numbers of partitions are 1, 8, 21, 34, etc., respectively: we can then as soon as the derivations giving the partitions

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into 1 part, 2 parts, 3 parts, etc., respectively, have been performed, verify that the right numbers 1, 8, 21, 34, etc., of terms have been obtained. The numbers are contained in the following table, each column of which is calculated from the preceding columns according to a rule which is easily obtained, and which is itself verified by the condition that the sums of the numbers in the several columns give the before mentioned series of numbers 1, 1, 2, 3, 5, 7, etc.

No. of Parts.	Partible Number.																		
	0	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18
1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1
2			1	1	2	2	3	3	4	4	5	5	6	6	7	7	8	8	9
3				1	1	2	3	4	5	7	8	10	12	14	16	19	21	24	27
4					1	1	2	3	5	6	9	11	15	18	23	27	34	39	47
5						1	1	2	3	5	7	10	13	18	23	30	37	47	57
6							1	1	2	3	5	7	11	14	20	26	35	44	58
7								1	1	2	3	5	7	11	15	21	28	38	49
8									1	1	2	3	5	7	11	15	22	29	40
9										1	1	2	3	5	7	11	15	22	30
10											1	1	2	3	5	7	11	15	22
11												1	1	2	3	5	7	11	15
12													1	1	2	3	5	7	11
13														1	1	2	3	5	7
14															1	1	2	3	5
15																1	1	2	3
16																	1	1	2
17																		1	1
18																			1
	1	1	2	3	5	7	11	15	22	30	42	56	77	101	135	176	231	297	385

The practical rule for the construction of the table thus is:— On a sheet of paper ruled in squares, and which is read as a continuous column from the bottom of one column to the top of the next column, form the terms by Arbogast's method as already explained; writing down in pencil a batch of terms, and counting them to see that the right number has been obtained, then, at the same time

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verifying the derivations, mark these over in ink; and so on with another batch of terms, until the whole number of the partitions of any particular number is obtained.

The foregoing series 1, 1, 2, 3, . . . 385, for the number of the partitions of the successive numbers 0, 1, 2, 3 . . . 18 is carried by Euler up to the number of partitions of 59, = 831820, see the paper *De Partitione Numerorum*, Op. Arith. Coll. I., bottom line of the table pp. 97–101: the continuation from the number 385 and for the partible numbers 19 to 30 is as follows:

19	20	21	22	23	24	25	26	27	28	29	30
490	627	792	1002	1255	1575	1958	2436	3010	3718	4565	5604

the whole number of terms 1, 1, . . . 5604 amounts to 28629, which at the rate of 500 to a page would occupy somewhat under 60 pages; or, at the rate here employed of 369 to a page, somewhat under 78 pages.

THE PARTITION TABLE, 0 TO 18.

0 . 3	4 . 5	6 . 7	7 . 8	8 . 9	9	9 . 10	10	10 . 11
0 1	**4** 5	**6** 11	cf	b^3g	bi	bc^4	bdg	c^5
1			de	bcf	ch	b^5e	bef	b^2f
			b^2f	bde	dg	b^4cd	c^2g	b^4ce
	e	g	bce	c^3e	ef	b^3c^3	cdf	b^4d^2
1 1	bd	bf	bd^2	cd^2	b^3h	b^6d	ce^2	b^3c^2d
	c^2	ce	c^2d	b^2f	bcg	b^3c^2	d^2e	b^2c^4
b	b^2c	d^2	b^3e	b^2ce	bdf	b^7c	b^3h	b^6e
	b^4	b^2e	b^2cd	b^2d^2	be^2	b^8	b^2cg	b^5cd
		bcd	bc^3	bc^2d	c^2f		b^2df	b^4c^3
2 2		c^3	b^4d	c^4	cde		b^2e^2	b^3d
	5 7	b^2d	b^3c^2	b^4e	d^3	**10** 42	bc^2f	b^6c^2
		b^2c^2	b^5c	b^3cd	b^2g		$bcde$	b^3c
c		b^4c	b^7	b^3c^3	b^2cf		bd^2	b^{10}
b^2	f	b^6		b^5d	b^2de	k	c^3e	
	be		**8** 22	b^4c^2	bc^2e	bj	c^2d^2	
3 3	cd	**7** 15		b^6c	bcd^2	ci	b^4g	**11** 56
	b^2d		i	b^8	c^3d	dh	b^3cf	
	bc^2		bh		b^4f	eg	b^3de	
d	b^3c		cg	**9** 30	b^3ce	f^2	b^2c^2e	l
bc	b^5	h	df		b^3d^2	b^2i	b^2cd^2	bk
b^3		bg	e^2	j	b^2c^2d	bch	bc^3d	cj

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11	11 . 12	12	12 . 13	13	13 . 14	14	14	14
di	b^5f	bcf	b^4d^2	bcg	bc^2d^2	gi	b^4k	c^3e
ek	b^5ca	bd^2f	b^3c^2d	bf^3	c^2d	b^2	b^3ej	c^2d^2
fg	b^3d^2	bde^2	b^3c^3	bd^2g	b^5h	b^2m	b^3ii	b^5i
bj	b^3c^2d	c^2g	b^3e	$bdef$	b^2cg	bcl	b^3ch	b^3ch
bci	b^3c^3	c^2df	b^2cd	be^2	b^3df	$beik$	b^4fg	b^3ig
bdh	b^3e	c^2e^2	b^4c^2	c^2h	b^3c^2	bej	b^3c^2i	b^3ef
beg	b^3cd	cd^2e	b^2d	c^2dg	b^3c^2f	bfi	b^2cdh	b^3c^2g
bf^2	b^2c^2	d^4	b^2c^2	c^2ef	b^3cde	bgh	b^2ceg	b^3cdf
c^2h	b^3d	b^3i	b^2ce	cd^2f	b^3d^2	c^2k	b^2ef^2	b^3ce^2
cdg	b^3e^2	b^3ch	b^2	cde^2	b^2c^2e	cdj	b^2d^2g	b^3d^2e
cef	b^2e	b^3dg		d^2e	$b^2c^2d^2$	cei	b^2def	b^3c^2f
d^2f	b^3	b^2ef	**13**	b^3j	b^2c^2d	cfh	b^2c^2	b^3c^2de
de^2		b^2c^2g		b^3ei	bc^4	cg^2	bc^2h	b^3cd^2
b^2i	**12**	b^2cdf	n	b^2dh	b^3g	d^2i	bc^2dg	b^2c^2e
b^2ch		b^2ce^2	bm	b^2eg	b^3ef	deh	bc^2ef	$b^2c^2d^2$
b^2dg	m	b^2d^2e	cl	b^2f^2	b^3de	dfg	bcd^2f	bc^2d
b^2f	bl	bc^2f	dk	b^2c^2h	b^3c^2e	c^2g	$bcde^2$	c^3
bc^2g	ek	bc^2de	ej	b^2cdg	b^3cd^2	ef^2	bd^2e	b^3h
$bcdf$	dj	bcd^2	fi	b^2cef	b^3c^2d	b^2l	c^2g	b^3eg
bce^2	ei	c^3e	gh	b^2d^2f	b^2c^3	b^2ek	c^2df	b^3df
bd^2e	fh	c^2d^2	b^2l	b^2de^2	b^4f	b^2dj	c^2e^2	b^3c^2
c^2f	g^2	b^2h	bek	bc^2g	b^3ce	b^3ei	c^2d^2e	b^3c^2f
c^2de	b^2k	b^3eg	bdj	bc^2df	b^3d^2	b^2fh	cd^3	b^3cde
cd^2	bej	b^3df	bei	bc^2e^2	b^3c^2d	b^2g^2	b^3j	b^3d^2
b^3h	bdi	b^3c^2	bfh	bcd^2e	b^3c^3	bc^2j	b^3ei	b^3c^2e
b^2eg	bch	b^2c^2f	bg^2	bd^3	$b^3e \cdot$	$bcdi$	b^3dh	$b^3c^2d^2$
b^2df	bfg	b^2cde	c^2j	c^3f	b^3cd	$bceh$	b^3eg	b^3c^3d
b^2c^2	c^2i	b^2d^2	cdi	c^2de	b^2c^2	$bcfg$	b^3f^2	b^2c^3
b^2c^2f	cdh	b^2ce	ceh	c^2d^2	$b^{10}d$	bd^2h	b^3c^2h	b^3g
b^2cde	ceg	$b^2c^2d^2$	cfg	b^3i	b^3e^2	$bdeg$	b^3cdg	b^3cf
b^2d^2	cf^2	bc^3d	d^2h	b^3ch	$b^{11}e$	bdf^2	b^2cef	b^3de
bc^2e	d^2g	c^4	deg	b^3dg	b^{13}	be^2f	b^3d^2f	b^3c^2e
bc^2d^2	def	b^3g	df^2	b^3ef		c^2i	b^3de^2	b^3cd^2
c^3d	e^3	b^3cf	e^2f	b^2c^2g	**14**	c^2dh	b^2c^2g	b^3c^2d
b^3g	b^2j	b^3dc	b^3k	b^3cdf	135	c^2eg	b^2c^2df	b^4c^3
b^3ef	b^2ei	b^3c^2e	b^2cj	b^3ce^2	o	c^2f^2	$b^2c^2e^2$	b^3f
b^3de	b^2dh	b^3cd^2	b^2di	b^3d^2e	bn	cd^2g	b^3cd^2e	b^3ce
b^2c^2e	b^2eg	b^3c^2d	b^2ch	b^2c^2f	cm	$cdef$	b^3d^4	b^3d^3
b^2cd^2	b^2f^2	b^2c^3	b^2fg	b^2c^2de	dl	ce^2	bc^4f	b^3c^2d
b^2c^2d	bc^2h	b^3f	bc^2i	b^2cd^2	ek	d^2f	bc^2de	b^3c^4
bc^5	$bcdg$	b^3ce	$bcdh$	bc^4e	fj	d^2e^2	bc^2d^2	$b^{10}e$

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14 . 15	15	15	15	15 . 16	16	16	16	16
b^9cd	b^3gh	$bcdef$	b^5f^2	b^4c^4d	cdl	ce^2f^2	cd^2e^3	b^5fg
b^8c^3	bc^3k	bce^3	b^4c^3h	b^3c^6	cek	d^3h	d^4e	b^4c^3i
$b^{11}d$	$bcdj$	bd^2f	b^4cdg	b^3g	cfj	d^2eg	b^5l	b^4cdh
$b^{10}c^2$	$bcei$	bd^2e^2	b^4ce^2f	b^5cf	cgi	d^2f^2	b^4ck	b^4ceg
$b^{12}c$	$bcfh$	c^4h	b^4d^2f	b^5de	ch^2	de^2f	b^4dj	b^4cf^2
b^{14}	bcg^2	c^3dg	b^4de^2	b^3c^2e	d^2k	e^4	b^4ei	b^4d^2g
15 176	bd^2i	c^3ef	b^3c^3g	b^3cd^2	dej	b^4m	b^4fh	b^4def
	$bdeh$	c^3d^2f	b^3c^3df	b^6c^3d	dfi	b^3cl	b^4g^2	b^4e^3
	$bdfg$	c^3de^2	$b^3c^2e^2$	b^5c^5	dgh	b^3dk	b^3c^2j	b^3c^3h
p	be^2g	cd^2e	b^3cd^2e	$b^{10}f$	e^2i	b^2ej	b^3cdi	b^3c^2dg
bo	bef^2	d^5	b^3d^4	b^3ce	efh	b^2fi	b^3ceh	b^3c^2ef
cn	c^2j	b^5k	b^3c^4f	b^3d^2	eg^2	b^2gh	b^2cfg	b^3cd^2f
dm	c^2di	b^4cj	b^3c^3de	b_8c^2d	f^2g	b^2c^2k	b^3d^2h	b^3cde^2
el	c^2eh	b^4di	$b^3c^2d^2$	b^7c^4	b^2n	b^2cdj	b^3deg	b^3d^2e
fk	c^2fg	b^4eh	bc^5e	$b^{11}e$	b^2cm	b^2cei	b^3df^2	b^3c^4g
gj	cd^2h	b^4fg	bc^4d^2	$b^{10}cd$	b^2dl	b^2cfh	b^3c^2f	b^3c^2df
hi	$cdeg$	b^3c^2i	c^6d	b^9c^2	b^2ek	b^2cg^2	b^3c^3i	$b^3c^3e^2$
b^2n	cdf^2	b^3cdh	b^7i	$b^{13}d$	b^2fj	b^2d^2i	b^3c^2dh	$b^3c^2d^2e$
bcm	ce^2f	b^3ceg	b^6ch	$b^{11}c^2$	b^2gi	b^2deh	b^3c^2eg	b^3cd^4
bdl	d^2g	b^3cf^2	b^6dg	$b^{13}c$	b^2k^2	b^2dfg	$b^3c^2f^2$	bc^5f
bek	d^2ef	b^2d^2g	b^6ef	b^{15}	bc^2l	b^2c^2g	b^2cd^2g	bc^4de
bfj	de^2	b^2def	b^5c^2g	**16** 231	$bcdk$	b^2ef^2	b^2cdef	bc^3d^3
bgi	b^4l	b^2e^3	b^5cdf		$bcej$	bc^2j	b^2ce^3	c^6e
bh^2	b^2ck	b^2c^2h	b^5ce^2		$bcfi$	bc^2di	b^2d^2f	c^5d^2
c^2l	b^2dj	b^2c^2dg	b^5d^2e	q	$begh$	bc^2eh	$b^2d^2e^2$	b^2j
cdk	b^2ei	b^2c^2ef	b^4c^2f	bp	bd^2j	bc^2fg	bc^4h	b^5ci
cej	b^2fh	b^2cd^2f	b^4c^2de	co	$bdei$	bcd^2h	bc^3dg	b^3dh
cfi	b^2g^2	b^2cde^2	b^4cd^2	dn	$bdfh$	$bcdeg$	bc^3ef	b^4eg
cgh	b^2c^2j	b^2d^2e	b^3c^4e	em	bdg^2	$bcdf^2$	bc^2d^2f	b^4f^2
d^2j	b^2cdi	bc^4g	$b^3c^2d^2$	fl	be^2h	bce^2f	bc^2de^2	b^5c^2h
dei	b^2ceh	bc^3df	b^2c^2d	gk	$befg$	bd^2g	bcd^2e	b^3cdg
dfh	b^2cfg	bc^3e^2	bc^7	hj	bf^2	bd^2ef	bd^5	b^5cef
dg^2	b^2d^2h	bc^2d^2e	b^5h	i^2	c^2k	bde^3	c^5g	b^5d^2f
e^2h	b^2deg	bcd^4	b^3cg	b^2o	c^2dj	c^4i	c^4df	b^5de^2
efg	b^2df^2	c^5f	b^3df	bcn	c^2ei	c^3dh	c^4e^2	b^4c^2g
f^3	b^2e^2f	c^4de	b^3e^2	bdm	c^2fh	c^2eg	c^3d^2e	b^4c^2df
b^2m	bc^2i	c^3d^2	b^6c^2f	bel	c^2g^2	c^3f^2	c^3d^4	$b^4c^3e^2$
b^2cl	bc^2dh	b^6j	b^6cde	bfk	cd^2i	c^3d^2g	b^6k	b^4cd^2e
b^2dk	bc^2eg	b^5ci	b^6d^2	bgj	$cdeh$	c^3def	b^5cj	b^4d^4
b^2ej	bc^2f^2	b^5dh	b^5c^2e	bhi	$cdfg$	c^3e^3	b^5di	b^3c^4f
b^2fi	bcd^2g	b^5eg	$b^5c^2d^2$	c^2m	ce^2g	cd^2f	b^5eh	b^5c^2de

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16	16 . 17	17	17	17	17	17	17	17 . 18
$b^2c^2d^2$	b^3c^2d	efi	def^2	c^2deg	bc^2e^2	bc^3g	b^3f^2	$b^2c^2d^2$
b^3c^2e	b^3c^4	egh	e^2f	c^2df^2	bcd^2f	bc^4df	b^4c^2h	b^4c^4d
$b^2c^4d^2$	$b^{12}e$	f^2h	b^4n	c^2e^2f	bcd^2e^2	bc^4e^2	b^4cdg	b^2c^6
bc^6d	$b^{11}cd$	fg^2	b^3em	cd^2g	bd^4e	bc^3d^2e	b^4cef	$b^{11}g$
c^8	$b^{10}c^3$	b^3o	b^3dl	cd^2ef	c^3h	bc^3d^4	b^4d^2f	$b^{10}cf$
b^9i	$b^{13}d$	b^3en	b^3ek	cde^2	c^4dg	c^4f	b^4de^2	$b^{10}de$
b^7ch	$b^{12}c^2$	b^3dm	b^3fj	d^4f	c^4ef	c^3de	b^3c^2g	b^2c^2e
b^7dg	$b^{14}c$	b^3el	b^2gi	d^2e^2	c^2d^2f	c^4d^2	b^3c^2df	b^2cd^2
b^7ef	b^{16}	b^3fk	b^2h^2	b^3m	c^2de^2	b^7k	$b^3c^2e^2$	b^4c^2d
b^6c^2g	17	b^3gj	b^2c^2l	b^4cl	c^2d^2e	b^6cj	b^3cd^2e	b^7c^3
b^6cdf	397	b^3hi	b^2cdk	b^4dk	cd^5	b^6di	b^3d^4	$b^{12}f$
b^6ce^2	bc^2m	b^2cej	b^4ej	b^4l	b^6eh	b^4c^4f	$b^{11}ce$	
b^6d^2e	r	$bcdl$	b^2cfi	b^4fi	b^5ck	b^6fg	b^4c^2de	$b^{11}d^2$
b^5c^3f	bq	$bcek$	b^2cgh	b^4gh	b^5dj	b^5c^2i	$b^4c^2d^2$	$b^{10}c^2d$
b^5c^2de	cp	$bcfj$	b^2d^2j	b^5c^2k	b^5ei	b^5cdh	b^5c^2e	b^9c^4
b^5cd^3	do	$begi$	b^2dei	b^3cdj	b^5fh	b^5ceg	$b^3c^4d^2$	$b^{13}e$
b^4c^4e	en	bch^2	b^2dfh	b^3cei	b^5g^2	b^5cf^2	b^2c^6d	$b^{13}cd$
$b^4c^2d^3$	fm	bd^2k	b^2dg^2	b^3cfh	b^4c^2j	b^5d^2g	bc^8	$b^{11}c^2$
b^3c^2d	gl	$bdej$	b^2c^2h	b^3cg^2	b^4cdi	b^5def	b^9i	$b^{14}d$
b^3c^7	hk	$bdfi$	b^2efg	b^3d^2i	b^4ceh	b^5c^3	b^8ch	$b^{13}c^3$
b^3h	ij	$bdgh$	b^2f^2	b^3deh	b^4cfg	b^4c^2h	b^8dg	$b^{15}c$
b^8cg	b^2p	bc^2i	bc^2k	b^3dfg	b^4d^2h	b^4c^2dg	b^8ef	b^{17}
b^8df	bco	$befh$	bc^2dj	b^2e^2g	b^4deg	b^4c^2ef	b^7c^2g	
b^8e^2	bdn	beg^2	bc^2ei	b^2ef^2	b^4df^2	b^4cd^2f	b^7cdf	18
b^7c^2f	bem	bf^2g	bc^2fh	b^2c^2j	b^4e^2f	b^4cde^2	b^7ce^2	385
b^7cde	bfl	c^2l	bc^2g^2	b^2c^2di	b^2c^2i	b^4d^2e	b^7d^2e	s
b^7d^3	bgk	c^2dk	bcd^2i	b^2c^2eh	b^3c^2dh	b^2c^4g	b^6c^2f	br
b^6c^2e	bhj	c^2ej	$bcdeh$	b^2c^2fg	b^3c^2eg	b^3c^2df	b^6c^2de	cq
$b^6c^2d^2$	bi^2	c^2fi	$bcdfg$	b^2cd^2h	$b^3c^2f^2$	$b^3c^4e^2$	b^6cd^3	dp
b^5c^4d	c^2n	c^2gh	bce^2g	b^2cdeg	b^2cd^2g	$b^2c^2d^2e$	b^5c^4e	eo
b^4c^6	cdm	cd^2j	$bcef^2$	b^2cdf^2	b^2cdef	b^2cd^4	$b^5c^2d^2$	fn
$b^{10}g$	cel	$cdei$	bd^2h	b^2ce^2f	b^2ce^2	b^2c^3f	b^4c^3d	gm
b^9cf	cfk	$cdfh$	bd^2eg	b^2d^2g	b^2d^2f	b^2c^4de	b^3c^7	hl
b^9de	cgj	cdg^2	bd^2f^2	b^2d^2ef	$b^2d^2e^2$	$b^2c^2d^3$	$b^{10}h$	ik
b^8c^2e	chi	ce^2h	bde^2f	b^2de^3	b^2c^4h	bc^6e	b^9cg	j^2
b^8cd^2	d^2l	$cefg$	be^4	bc^4i	b^2c^2dg	bc^5d^2	b^9df	b^2q
b^7c^2d	dek	cf^2	c^4j	bc^2dh	b^2c^2ef	c^2d	b^8e^2	bcp
b^6c^5	dfj	d^2i	c^2di	bc^2eg	$b^2c^2d^2f$	b^2j	b^8c^2f	bdo
$b^{11}f$	dgi	d^2eh	c^2eh	bc^2f^2	$b^2c^2de^2$	b^2ci	b^8cde	ben
$b^{10}ce$	dh^2	d^2fg	c^2fg	bc^2d^2g	b^2cd^2e	b^2dh	b^8d^3	bfm
$b^{10}d^2$	e^2j	de^2g	c^2d^2h	bc^2def	b^2d^3	b^2eg	b^2c^2e	bgl

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18	18	18	18	18	18	18	18	18
bhk	$befi$	b^3dej	d^3ef	bc^3deg	b^3cdf^2	b^4c^3i	b^3cd^2f	b^4c^3g
bij	$begh$	b^3dfi	d^3e^2	bc^3df^2	b^3ce^2f	b^4c^2dh	b^3cde^2	b^3cdf
c^2o	bf^2h	b^3dgh	b^3n	bc^2e^2f	b^3d^2g	b^4c^2eg	b^3d^2e	b^3ce^2
cdn	bfg^2	b^3e^2i	b^4cm	bcd^2g	b^3d^2ef	$b^4c^2f^2$	b^4c^4g	b^6d^2e
cem	c^2m	b^3efh	b^4dl	bcd^2ef	b^6de^2	b^4cd^2g	b^4c^2df	b^7c^2f
cfl	c^2dl	b^3eg^2	b^4ek	$bcde^2$	b^5c^4i	b^4cdef	$b^4c^3e^2$	b^7c^2de
cgk	c^2ek	b^2f^2g	b^4fj	bd^4f	b^5c^2dh	b^4ce^2	$b^4c^2d^2e$	b^7cd^2
chj	c^2fj	bc^2l	b^4gi	bd^2e^2	b^5c^2eg	b^4d^2f	b^4cd^4	b^6c^4e
ci^2	c^2gi	bc^2dk	b^4h^2	c^2i	$b^3c^2f^2$	$b^4d^2e^2$	b^3c^2f	$b^6c^2d^2$
d^2m	c^2h^2	bc^2ej	b^2c^2l	c^4dh	$b^3c^2d^2g$	b^2c^4h	b^3c^4de	b^5c^2d
del	cd^2k	bc^2fi	b^3cdk	c^4eg	b^3c^2def	b^2c^2dg	$b^2c^2d^2$	b^4c^3
dfk	$cdej$	bc^2gh	b^3cej	c^4f^2	$b^3c^2e^2$	b^2c^2ef	b^2c^4e	$b^{11}h$
dgj	$cdfi$	bcd^2j	b^3cfi	c^3d^2g	b^3cd^2f	$b^2c^2d^2f$	$b^2c^2d^2$	$b^{10}cg$
dhi	$cdgh$	$bcdei$	b^3cgh	c^3def	$b^3cd^2e^2$	$b^2c^2de^2$	bc^3d	$b^{10}df$
e^2k	ce^2i	$bcdfh$	b^3d^2j	c^2e^2	b^3d^4e	b^2cd^2e	c^2	$b^{10}e^2$
efj	$cefh$	$bcdg^2$	b^3dei	c^2d^2f	bc^5h	b^3d^5	b^4j	b^3c^2f
egi	ceg^2	bce^2h	b^3dfh	$c^2d^2e^2$	bc^4dg	b^3c^3g	b^3ci	b^3cde
eh^2	cf^2g	$bcefg$	b^3dg^2	cd^4e	bc^4ef	b^2c^4df	b^3dh	b^3d^2
f^2i	d^2j	bcf^2	b^2e^2h	d^6	bc^3d^2f	$b^2c^4e^2$	b^4eg	b^3c^2e
fgh	d^2ei	bd^2i	b^2efg	b^4m	bc^3de^2	$b^2c^3d^2e$	b^3f^2	$b^3c^2d^2$
g^2	d^2fh	bd^2eh	b^3f^2	b^4cl	bc^3d^2e	$b^2c^2d^4$	b^2c^2h	b^2c^4d
b^2p	d^2g^2	bd^2fg	b^2c^2k	b^4dk	bcd^5	bc^6f	b^2cdg	b^6c^3
b^2co	de^2h	bde^2g	b^2c^2dj	b^4ej	c^3g	bc^5de	b^2cef	$b^{12}g$
b^2dn	$defg$	$bdef^2$	b^2c^2ei	b^4fi	c^4df	bc^4d^2	b^2d^2f	$b^{11}cf$
b^2em	df^2	be^2f	b^2c^2fh	b^4gh	c^4e^2	c^3e	b^2de^2	$b^{11}de$
b^2fl	e^2g	c^4k	$b^2c^2g^2$	b^4c^2k	c^4d^2e	c^4d^2	b^6c^2g	$b^{10}c^2e$
b^2gk	e^2f^2	c^3dj	b^2cd^2i	b^4cdj	c^3d^4	b^6k	b^6c^2df	$b^{10}cd^2$
b^2hj	b^4o	c^3ei	b^2cdeh	b^4cei	b^7l	b^7cj	$b^6c^2e^2$	b^2c^3d
b^2i^2	b^2cn	c^3fh	b^2cdfg	b^4cfh	b^6ck	b^7di	b^6cd^2e	b^6c^3
bc^2n	b^2dm	c^3g^2	b^2ce^2g	b^4cg^2	b^6dj	b^7eh	b^6d^4	$b^{12}f$
$bcdm$	b^2el	c^2d^2i	b^2cef^2	b^4d^2i	b^6ei	b^7fg	b^5c^4f	$b^{12}ce$
$bcel$	b^2fk	c^2deh	b^2d^2h	b^4deh	b^6fh	b^6c^2i	b^5c^2de	$b^{12}d^2$
$bcfk$	b^2gj	c^2dfg	b^2d^2eg	b^4dfg	b^6g^2	b^6cdh	$b^5c^2d^2$	$b^{11}c^2d$
$bcgj$	b^2hi	c^2e^2g	$b^2d^2f^2$	b^4e^2g	b^6c^2j	b^6ceg	b^4c^5e	$b^{10}c^4$
$bchi$	b^2c^2m	c^2ef^2	b^2de^2f	b^4ef^2	b^6cdi	b^6cf^2	$b^4c^4d^2$	$b^{14}e$
bd^2l	b^2cdl	cd^2h	b^2e^4	b^2c^2j	b^6ceh	b^6d^2g	b^5c^6d	$b^{12}cd$
$bdek$	b^2cek	cd^2eg	bc^4j	b^2c^2di	b^5cfg	b^6def	b^2c^8	$b^{12}c^2$
$bdfj$	b^2cfj	cd^2f^2	bc^2di	b^2c^2eh	b^5d^2h	b^6e^3	$b^{10}i$	$b^{13}d$
$bdgi$	b^2cgi	cde^2f	bc^2eh	b^2c^2fg	b^5deg	b^5c^3h	b^3ch	$b^{14}c^2$
bdh^2	b^2ch^2	ce^4	bc^2fg	b^2cd^2h	b^5df^2	b^5c^3dg	b^3dg	$b^{16}c$
be^2j	b^2d^2k	d^4g	bc^2d^2h	b^2cdeg	b^5e^2f	b^5c^3ef	b^3ef	b^{16}

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Note on Hansen's General Formulae for Perturbations.

By G. W. Hill.

The last form in which Hansen expressed the perturbations of the mean anomaly and equated radius vector is exhibited by the following equations:

$$n_0 z = n_0 t + c_0 + \int \left\{ W + \frac{h_0}{h} \left(\frac{\nu}{1+\nu} \right)^2 \right\} n_0 dt,$$

$$\nu = C - \frac{1}{2} \int \left(\frac{dW}{dz} \right) dt,$$

(Equations 36 and 37, p. 97.)*

It will be perceived that the right-hand member of the first of these involves three quantities, viz. W, ν and $\frac{h_0}{h}$. But the last of these quantities has no share in defining the position of the body, and it is desirable to get rid of it, provided that can be done without complicating the equation. This is readily accomplished by means of the equation (33, p. 95)

$$\frac{dz}{dt} = \frac{h_0}{h (1+\nu)^2}.$$

The result is

$$n_0 z = n_0 t + c_0 + \int \frac{W + \nu^2}{1 - \nu^2} n_0 dt.$$

Why Hansen has not put the equation in this form I cannot imagine; the advantage, not only as regards simplicity of expression, but also in point of ease of computation, is evident.

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* See *Auseinandersetzung einer zweckmässigen Methode zur Berechnung der absoluten Störungen der kleinen Planeten. Von P. A. Hansen. Erste Abhandlung.* (*Abhandlungen der Königlichen Sächsischen Gesellschaft der Wissenschaften. Band* III.) The numbering of the equations and the paging are from this volume.

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HANSEN develops $\overline{W}$ by TAYLOR'S theorem, and, limiting ourselves to the second power of the disturbing force, we have

$$\overline{W} = \overline{W}_0 + \left(\frac{d\overline{W}_0}{d\gamma}\right) n_0 \delta z = \overline{W}_0 - 2\frac{dz}{dt}\delta z .$$

When this value is substituted for $\overline{W}$ in the equation for $n_0 z$, we have a differential equation of the first order and degree for the determination of δz, the integral of which is well known. Terms of three dimensions with respect to disturbing forces being neglected, this procedure furnishes the equation

$$n_0 \delta z = (1 - 2\nu) \int [(1 + 2\nu)\, \overline{W}_0 + \nu^2]\, n_0 dt ,$$

which, however, is without interest other than analytical, as its use involves more labor than that of the equation given by HANSEN.

HANSEN'S equation for the determination of ν has the disadvantage of not affording the constant term of this quantity, and is inconvenient in computing the portion, of the form

$$At + Bt^2 + Ct^3 + \ldots ,$$

which is independent of the arguments g, g', &c., as the values of A, B, &c., must be determined to a degree of accuracy much beyond what is necessary in the case of the other terms. As all the arbitrary constants admissible have been introduced by the integrations which give z, it is evident there must exist an equation determining ν without additional integrations. HANSEN has virtually employed this in the place where he shows how the constant term of ν is to be obtained, but has nowhere given it explicitly. This lacuna I propose to fill here.

The equation 39, p. 97,

$$W_0 = 2\frac{h}{h_0} - \frac{h_0}{h} - 1 + 2\frac{h}{h_0}\xi\frac{\rho}{a_0}\cos\omega + 2\frac{h}{h_0}\eta\frac{\rho}{a_0}\sin\omega ,$$

may be employed to discover the value of $\frac{h}{h_0}$. The known expressions for $\frac{\rho}{a_0}\cos\omega$ and $\frac{\rho}{a_0}\sin\omega$ are

$$\frac{\rho}{a_0}\cos\omega = -\frac{3}{2}e + \left(J_{\frac{1}{2}}^{(0)} - J_{\frac{1}{2}}^{(2)}\right)\cos\gamma + \frac{1}{2}\left(J_e^{(1)} - J_e^{(3)}\right)\cos 2\gamma + \ldots ,$$

$$\frac{\rho}{a_0}\sin\omega = \left(J_{\frac{1}{2}}^{(0)} + J_{\frac{1}{2}}^{(2)}\right)\sin\gamma + \frac{1}{2}\left(J_e^{(1)} + J_e^{(3)}\right)\sin 2\gamma + \ldots ,$$

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where HANSEN's notation for the BESSELIAN function is employed, and the subscript zero, which properly belongs to e, is for convenience in writing, omitted. In his memoirs, where the mean anomaly is employed as the independent variable, HANSEN directs to compute only the parts of W_0 which are independent of γ or which have $\pm\gamma$ in their arguments; that is, the parts which have the form

$$X_0 + X_1 \cos\gamma + X_2 \sin\gamma .$$

X_0, X_1 and X_2 being independent of γ.

It will be easily perceived that, if we put

$$P = \frac{3}{2} J_1^{2} - J_2^{2} ,$$

P being thus a constant, the three first terms of W_0 must have the value

$$2\frac{h}{h_0} - \frac{h_0}{h} - 1 = X_0 + PX_1 .$$

In this equation we may substitute for $\frac{h_0}{h}$ its value obtained from equation 33, and thus we obtain

$$(1+\nu)^2\left(1+\frac{d.\delta z}{dt}\right)^{-2} - (1+\nu)^3\left(1+\frac{d.\delta z}{dt}\right) - 1 = X_0 + PX_1 .$$

This equation, when $\frac{d.\delta z}{dt}$ is known, gives ν without additional integrations.

To put it into a form suitable for computation, we add to each member such a quantity as will make the first equal to -6ν, then dividing both members by 6 we get

$$\nu = -\frac{1}{6}\left[X_0 + PX_1\right] - \frac{1}{2}\left[(1+\nu)^2\frac{d.\delta z}{dt} + \nu^2\right] + \frac{\left[(1+\nu)^2\frac{d.\delta z}{dt} + 2\nu + \nu^2\right]^2}{3(1+\nu)^3\left(1+\frac{d.\delta z}{dt}\right)} .$$

This equation is rigorous. If we may restrict ourselves to terms of the first order with respect to disturbing forces, it reduces to

$$\nu = -\frac{1}{6}\left[X_0 + PX_1\right] - \frac{1}{2}\frac{d.\delta z}{dt} ,$$

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or, if terms of the second order must be included, to

$$v = -\frac{1}{6}\left[X_0 + PX_1\right] - \frac{1}{2}\frac{d.\delta z}{dt} + \frac{1}{3}\left[\frac{d.\delta z}{dt} + \frac{1}{2}v\right]^2 + \frac{3}{4}v^2.$$

The function usually tabulated is com. log $(1+v)$; and we have com. log $(1+v) = M\left\{-\frac{1}{6}\left[X_0 + PX_1\right] - \frac{1}{2}\frac{d.\delta z}{dt} + \frac{1}{3}\left[\frac{d.\delta z}{dt} + \frac{1}{2}v\right]^2 + \frac{1}{4}v^2\right\}$, M being the modulus of common logarithms.

These equations are as readily used as those given by HANSEN, and are free from the disadvantages, previously mentioned, which belong to the latter. All the quantities involved, except X_1, have already been obtained in the computation of δz. Also X_1 is readily got by putting $\gamma = 0$ in the terms of W_0 which involve this quantity, and summing two and two together the terms which result.

WASHINGTON, D. C., *December* 17, 1881.

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On the Solution of a Certain Class of Difference or Differential Equations.

By A. [illegible]

I have [illegible] Mr. W. [illegible] Boole's Treatise on [illegible] Differences [illegible]. I was [illegible] to find that the [illegible] a, b, c [illegible] [illegible] the [illegible] of the [illegible] [illegible] Boole's [illegible] to [illegible] the [illegible] [illegible]. Take [illegible]

$$\begin{matrix} u_x & u_{x+1} & \cdots & u_{x+r} \\ u_{x+1} & u_{x+2} & \cdots & u_{x+r+1} \\ u_{x+2} & u_{x+3} & \cdots & u_{x+r+2} \\ \cdots & \cdots & \cdots & \cdots \\ \cdots & \cdots & \cdots & \cdots \\ u_{x+r} & u_{x+r+1} & \cdots & u_{x+2r} \end{matrix}$$

which is of the r^{th} degree and $2r^{th}$ order.

To fix the ideas, let us consider the simple case

$$u_x u_{x+2} - u_{x+1}^2 = I^x m^x,$$

of which, when $I = 0$, the solution is $u_x = A\alpha^x$, A and α being both arbitrary, but for I not zero is expressed by $u_x = \pm (A\alpha^x + B\beta^x)$ with the conditions

$$\alpha\beta = m, \quad AB(\alpha - \beta)^2 = I^x$$

which solution in an *obiter dictum* I may remark may easily be converted into the simpler and more explicit form

$$(\sin \beta)^2 u_x^2 + I^x (\sin \alpha + x)^2 m^{x-1} = 0$$

where α, β are arbitrary constants.

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If we proceed now to verify the solution in its original form, we shall immediately be led to perceive a certain generalization which the given equation may be made to undergo without ceasing to be soluble—the solution however becoming narrowed from a general to a special one: whether particular or singular I shall not discuss.

If we write $u_x = A\alpha^x + B\beta^x$, the determinant becomes

$$\begin{vmatrix} A\alpha^x + B\beta^x & A\alpha^{x+1} + B\beta^{x+1} \\ A\alpha^{x+1} + B\beta^{x+1} & A\alpha^{x+2} + B\beta^{x+2} \end{vmatrix}$$

which is equal to $AB(\alpha - \beta)^2(\alpha\beta)^x$; this is the verification spoken of: but, as a consequence, it is apparent that we must have

$$\begin{vmatrix} A\alpha^x + B\beta^x + C\gamma^x, & A\alpha^{x+1} + B\beta^{x+1} + C\gamma^{x+1} \\ A\alpha^{x+1} + B\beta^{x+1} + C\gamma^{x+1} & A\alpha^{x+2} + B\beta^{x+2} + C\gamma^{x+2} \end{vmatrix}$$
$$= AB(\alpha - \beta)^2(\alpha\beta)^x + BC(\beta - \gamma)^2(\beta\gamma)^x + CA(\gamma - \alpha)^2(\gamma\alpha)^x.$$

Hence we can solve the equation

$$u_x u_{x+2} - u_{x+1}^2 = Pl^x + Qm^x + Rn^x,$$

viz. we may write

$$u_x + A\alpha^x + B\beta^x + C\gamma^x = 0,$$

where

$$\beta\gamma = l, \quad \gamma\alpha = m, \quad \alpha\beta = n,$$

$$AB(\alpha - \beta)^2 = R, \quad BC(\beta - \gamma)^2 = P, \quad CA(\gamma - \alpha)^2 = Q,$$

that is to say

$$\alpha = \sqrt{\frac{mn}{l}}, \quad \beta = \sqrt{\frac{nl}{m}}, \quad \gamma = \sqrt{\frac{lm}{n}},$$

$$A = \sqrt{\frac{QR}{P}} \frac{(\beta - \gamma)}{(\alpha - \beta)(\alpha - \gamma)}, \quad B = \sqrt{\frac{RP}{Q}} \frac{(\gamma - \alpha)}{(\beta - \alpha)(\beta - \gamma)}, \quad C = \sqrt{\frac{PQ}{R}} \frac{(\alpha - \beta)}{(\gamma - \alpha)(\gamma - \beta)}.$$

or calling

$$\sqrt{lmn} = g, \quad \sqrt{PQR} = G,$$

$$\alpha = \frac{g}{l}, \quad \beta = \frac{g}{m}, \quad \gamma = \frac{g}{n},$$

$$A = \frac{G}{g} \cdot \frac{(n - m)l^2}{(l - m)(l - n)P}, \quad B = \frac{G}{g} \cdot \frac{(l - n)m^2}{(m - n)(m - l)Q}, \quad C = \frac{G}{g} \cdot \frac{(m - l)n^2}{(n - l)(n - m)R}.$$

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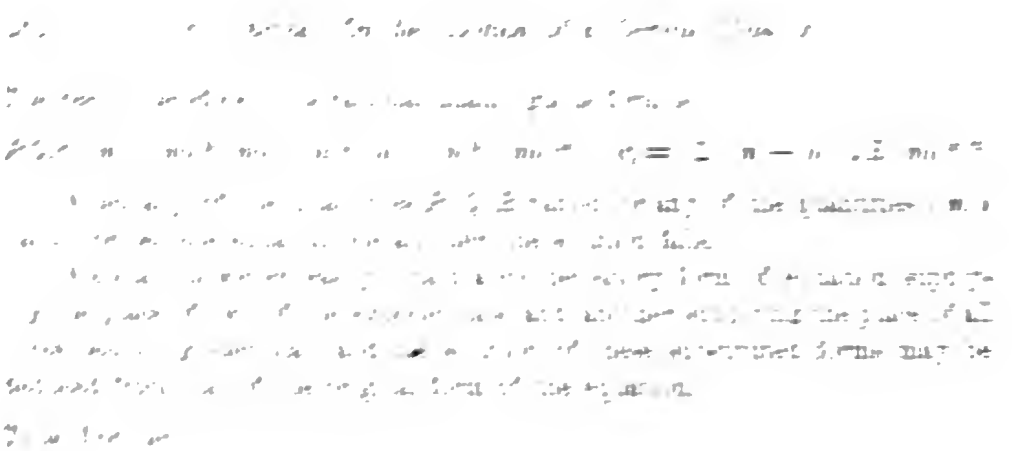

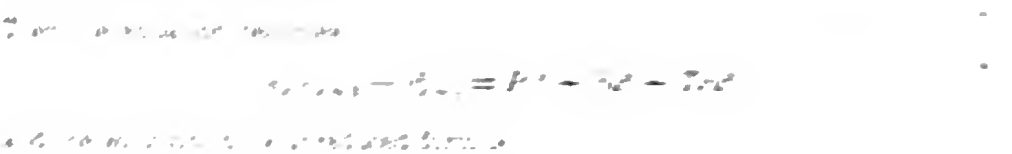

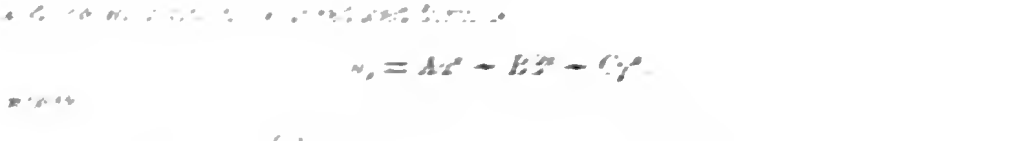

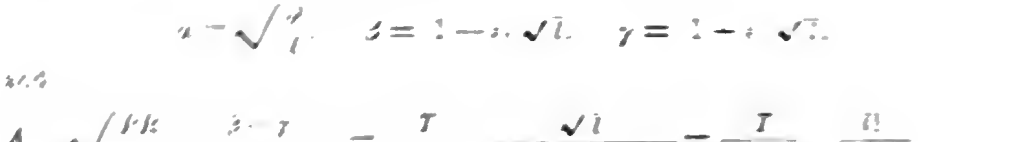

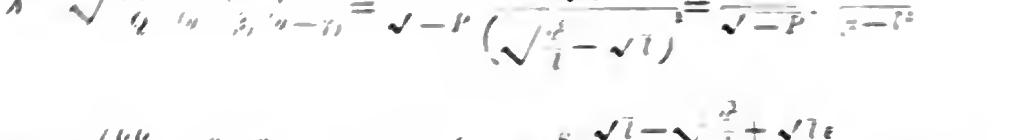

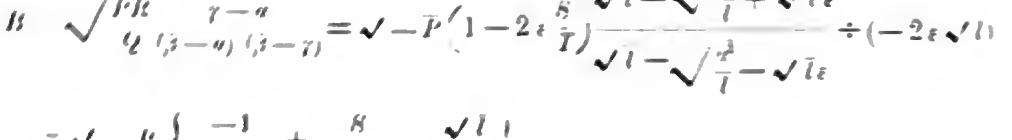

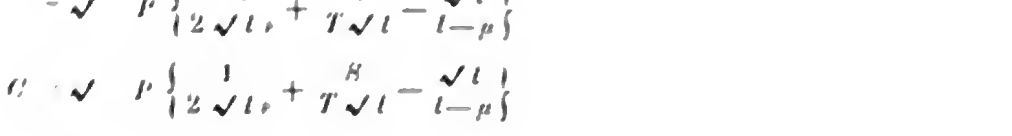

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Hence $$B\beta^x + C\gamma^x = \sqrt{-P}\, l^{\frac{x-1}{2}} \left\{ \begin{array}{l} (1+x\varepsilon)\left(\frac{1}{2\varepsilon} + \frac{S}{T} - \frac{l}{l-\mu} \right) \\ +(1-x\varepsilon)\left(-\frac{1}{2\varepsilon} + \frac{S}{T} - \frac{l}{l-\mu} \right) \end{array} \right\}$$

$$= \sqrt{-P} \left\{ 2\left(\frac{S}{T} - \frac{l}{l-\mu} \right) + x \right\} l^{\frac{x-1}{2}};$$

so that

$$\sqrt{-lP}\, u_x = T\left(\frac{l}{\mu - l} \right)^2 \left(\frac{\mu^2}{l} \right)^{\frac{x}{2}} - P\left(\frac{2S}{T} - \frac{2l}{l-\mu} + x \right) l^{\frac{x}{2}}$$

or

$$Pl^{x+1} u_x^2 + \left\{ T\left(\frac{l}{\mu - l} \right)^2 \mu^x - P\left(\frac{2S}{T} + \frac{2l}{\mu - l} + x \right) l^x \right\}^2 = 0$$

will satisfy the given equation

$$u_x\, u_{x+2} - u_{x+1}^2 = Pl^x + S\mu^x + Tx\mu^x.$$

When $T = 0$ the solution fails, as we know *à priori* it ought to do.

When $S = 0$ it takes the form

$$Pl^{x+1} u_x^2 + \left\{ T\left(\frac{l}{\mu - l} \right)^2 \mu^x - P\left(\frac{2l}{\mu - l} + x \right) l^x \right\}^2 = 0.$$

We might, by an analogous process, writing $(1+\varepsilon)$, $(1+\rho\varepsilon)$, $(1+\rho^2\varepsilon)$ in lieu of l, m, n, and giving P, Q, R appropriate values involving ε^2 as well as ε, render ΣPl^x a finite function of the form $(S + Tx + Ux^2)\lambda^x$, and deduce the solution of $u_x\, u_{x+2} - u_{x+1}^2 = (S + Tx + Ux^2)\lambda^x$ as a particular case of the solution of the general equation. But as we can easily see that the unreduced form of the solution must be $u_x = \lambda^{\frac{x}{2}}(A + Bx + Cx^2)$, it will be easier to find A, B, C immediately from the equation

$$\begin{vmatrix} A + Bx + Cx^2 & A + B(x+1) + C(x+1)^2 \\ A + B(x+1) + C(x+1)^2 & A + B(x+2) + C(x+2)^2 \end{vmatrix}$$

or
$$\begin{vmatrix} A + Bx + Cx^2 & A + B(x+1) + C(x+1)^2 \\ B + C + 2x & B + 3C + 2Cx \end{vmatrix}$$

or
$$\begin{vmatrix} A + Bx + Cx^2 & B + C + 2Cx \\ B + C + 2Cx & 2C \end{vmatrix} = S + Tx + Ux^2.$$

Hence $$-2C^2 = U,\ -2BC - 4C^2 = T,\ 2AC - (B+C)^2 = S.$$

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[illegible]

$$C = \sqrt{\quad} \quad B = -2C - \frac{T}{\sqrt{\quad}} = -\sqrt{\quad} - \frac{T}{\sqrt{\quad}} = \frac{\quad}{\sqrt{\quad}}$$

$$A = \frac{\quad}{\quad} = \frac{\quad}{\sqrt{\quad}} = \frac{\quad}{\quad}$$

or

$$[illegible]$$

is the required solution of the given equation.

The method may obviously be extended to any equation of the given form: that is to say when the [illegible] determinant which it contains is of the degree i and is equated to $i+1$ multiples of exponentials each of the form $Pe^{\quad}$ an integral of it can be found, and if these i exponentials be subdivided into partial groups of s, s', s'' ... terms in a group then instead of the s multiples of exponentials belonging to any group may be substituted $(P_1 + P_2\quad + P_3\quad^2 + \ldots + P_s\quad^{s-1})e^{\quad}$, and the solution of the equation so modified may be deduced from the solution first mentioned as a particular case thereof.

It will be sufficient for all reasonable purposes of illustration briefly to consider the case of

$$\begin{vmatrix} u_x & u_{x+1} & u_{x+2} \\ u_{x+1} & u_{x+2} & u_{x+3} \\ u_{x+2} & u_{x+3} & u_{x+4} \end{vmatrix} = Pl^x + Qm^x + Rn^x + Sp^x.$$

An integral of this may be found by writing

$$u_x = A\alpha^x + B\beta^x + C\gamma^x + D\delta^x,$$

where

$$\alpha\beta\gamma\delta = l, \quad \alpha\beta\gamma = m, \quad \alpha\beta\delta = n, \quad \alpha\beta\gamma = p,$$

$$BCD\zeta(\beta, \gamma, \delta) = P, \quad ACD\zeta(\alpha, \gamma, \delta) = Q, \quad ABD\zeta(\alpha, \beta, \delta) = R,$$
$$ABC\zeta(\alpha, \beta, \gamma) = S,$$

ζ meaning the product of the squared differences of the letters which it governs.

We have thus

$$\alpha = \frac{g}{l}, \quad \beta = \frac{g}{m}, \quad \gamma = \frac{g}{n}, \quad \delta = \frac{g}{p},$$

where

$$g = \sqrt[4]{lmnp}$$

and

$$A^2B^2C^2D^2[\zeta(\alpha, \beta, \gamma, \delta)]^2 = PQRS,$$

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so that writing

$$G = \left\{ \frac{PQRS}{[\zeta(\alpha, \beta, \gamma, \delta)]^2} \right\}^{\frac{1}{4}} = \frac{1}{g^3} \frac{(PQRS)^{\frac{1}{4}}}{\left\{ \zeta\left(\frac{1}{l}, \frac{1}{m}, \frac{1}{n}, \frac{1}{p}\right) \right\}^{\frac{1}{4}}}$$

$A = \zeta(\beta, \gamma, \delta)\frac{G}{P}$; $B = \zeta(\alpha, \gamma, \delta)\frac{G}{Q}$; $C = \zeta(\alpha, \beta, \delta)\frac{G}{R}$; $D = \zeta(\alpha, \beta, \gamma)\frac{G}{S}$;

and thus

$$(PQRS)^2 (lmnp)^x \left\{ \zeta\left(\frac{1}{l}, \frac{1}{m}, \frac{1}{n}, \frac{1}{p}\right) \right\}^2 u_x^2 = (lmnp)^x \{\Sigma QRS\zeta(\beta, \gamma, \delta) l^{-x}\}^2$$

or

$$\left\{ PQRS\zeta\left(\frac{1}{l}, \frac{1}{m}, \frac{1}{n}, \frac{1}{p}\right) \right\}^2 u_x^2 = (lmnp)^{x-2} \left\{ \Sigma QRS\zeta\left(\frac{1}{m}, \frac{1}{n}, \frac{1}{p}\right) l^{-x} \right\}^2.$$

It is scarcely necessary to add that all the above conclusions continue to hold, when, on the left hand side of the equation for u_{x+h} we write $\left(\frac{d}{dx}\right)^h y$ and at the same time for any exponential l^x on the right hand side substitute e^{lx}.

Thus for instance we may in general find an integral of

$$yy'' - y'^2 = Ae^{kx} + Be^{kx}\cos(\alpha x + \beta)$$

or again of

$$(yy'' - y'^2)y'''' - y(y''')^2 + 2y'y''y''' - y''^3 = Ae^{kx}\cos(\alpha x + \beta) + Be^{kx}\cos(\gamma x + \delta).$$

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On the Analytical Forms called Trees.

By Professor Cayley.

A tree of N knots is any one of 2 knots, 3 knots, ... N knots which may be regarded as a system of N knots connected by lines, and which is then called a tree-form. The centre (or bicentre) of a tree is a knot (or line) such that the number of knots on each branch proceeding from it is ≤ ½N; and if we number the N knots of a tree-form in such manner that the number of knots on each branch proceeding from the knot 1 is ≤ ½N, and that the number of knots on each branch proceeding from the knot 2 is ≤ ½N, then the knot 1 is the centre, and the line 12 is the bicentre. We have to find the number of distinct trees with N knots.

I have in my paper "On the Theory of the Analytical Forms called Trees," *Phil. Mag.* [4] 13 (1857), pp. 172–176, given the solution of the first question: viz. if ψ_n denote the number of the tree-forms with N knots, then the successive numbers ψ_1, ψ_2, ψ_3, &c. are given by the formula

$$\psi_1 + x\psi_2 + x^2\psi_3 + \ldots = (1-x)^{-\psi_1}(1-x^2)^{-\psi_2}(1-x^3)^{-\psi_3}\ldots$$

viz. we thence find

number of	ψ	1	2	3	4	5	6	7	8	9	10	11	12	13
	ψ	1	1	2	4	9	20	48	115	286	719	1842	4766	12486

And I have, in the paper "On the Analytical Forms called Trees, with Applications to the Theory of Chemical Combinations," *Brit. Assoc. Report*, 1875, pp. 257–305, also shown how by the consideration of the centre or bicentre "of length" we can obtain formulæ for the number of central and bicentral trees, that is for the number of distinct trees, with N knots: the numerical result obtained for the total number of distinct trees with N knots is given as follows:

No. of Knots	1	2	3	4	5	6	7	8	9	10	11	12	13
No. of Central Trees	1	0	1	1	2	3	7	12	27	55	127	284	682
" Bicentral "	0	1	0	1	1	3	4	11	20	51	108	267	619
Total	1	1	1	2	3	6	11	23	47	106	235	551	1301

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But a more simple solution is obtained by the consideration of the centre or bicentre "of number." A tree of an odd number N of knots has a centre of number, and a tree of an even number N of knots has a centre or else a bicentre of number. To explain this notion (due to M. Camille Jordan) we consider the branches which proceed from any knot, and (excluding always this knot itself) we count the number of the knots upon the several branches; say these numbers are α, β, γ, δ, ε, etc., where of course $\alpha + \beta + \gamma + \delta + \varepsilon + \text{etc.} = N - 1$. If N is even we may have, say $\alpha = \frac{1}{2}N$; and then $\beta + \gamma + \delta + \varepsilon + \text{etc.} = \frac{1}{2}N - 1$, viz. α is larger by unity than the sum of the remaining numbers: the branch with α knots, or the number α, is said to be "merely dominant." If N be odd, we cannot of course have $\alpha = \frac{1}{2}N$, but we may have $\alpha > \frac{1}{2}N$; here α exceeds by 2 at least the sum of the other numbers; and the branch with α knots, or the number α, is said to be "predominant." In every other case, viz. in the case where each number α is less than $\frac{1}{2}N$, (and where consequently the largest number α does not exceed the sum of the remaining numbers), the several branches, or the numbers α, β, γ, etc., are said to be subequal. And we have the theorem: first when N is odd, there is always one knot (and only one knot) for which the branches are subequal: such knot is called the centre of number. Secondly when N is even; either there is one knot (and only one knot) for which the branches are subequal; and such knot is then called the centre of number; or else there is no such knot, but there are two adjacent knots (and no other knot) each having a merely-dominant branch; such two knots are called the bicentre of number, and each of them separately is a half-centre.

Considering now the trees with N knots as springing from a centre or a bicentre of number, and writing ψ_N for the whole number of distinct trees with N knots, we readily obtain these in terms of the foregoing numbers ϕ_1, ϕ_2, ϕ_3, etc., viz. we have

$$\begin{aligned}
\psi_1 &= 1, \\
\psi_2 &= \tfrac{1}{2}\phi_1(\phi_1 + 1), \\
\psi_3 &= \text{coeff. } x^3 \text{ in } (1-x)^{-\phi_1}, \\
\psi_4 &= \tfrac{1}{2}\phi_2(\phi_2 + 1) + \text{coeff. } x^4 \text{ in } (1-x)^{-\phi_1}, \\
\psi_5 &= \text{coeff. } x^5 \text{ in } (1-x)^{-\phi_1}(1-x^2)^{-\phi_2}, \\
\psi_6 &= \tfrac{1}{2}\phi_3(\phi_3 + 1) + \text{coeff. } x^6 \text{ in } (1-x)^{-\phi_1}(1-x^2)^{-\phi_2}, \\
\psi_7 &= \text{coeff. } x^7 \text{ in } (1-x)^{-\phi_1}(1-x^2)^{-\phi_3}(1-x^3)^{-\phi_3},
\end{aligned}$$

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Notes.

I.

On Symbols of Operation.

By Professor Crofton, F. R. S.

To prove that, ϕ being any function of D, *i. e.* $\frac{d}{dx}$,

$$e^{x\phi(D)}e^{\lambda x} = e^{\lambda x}, \tag{1}$$

where λ is a constant determined from

$$\psi(\lambda) = 1 + \psi(h), \tag{2}$$

the function ψ being defined by

$$\psi(x) = \int \frac{dx}{\varphi(x)}. \tag{3}$$

The above theorem might be made to follow from principles given in a paper by me in the Proceedings of the London Mathematical Society, April 1881; but the following method may be also employed.

Let $$u = e^{kx\phi(D)}e^{hx};$$

differentiating with regard to h,

$$\frac{du}{dh} = e^{kx\phi D}xe^{hx},$$

also
$$\frac{du}{dk} = e^{kx\phi D}x\phi(D)e^{hx}$$
$$= \phi(h)e^{kx\phi D}xe^{hx}.$$

We have thus a partial differential equation

$$\frac{du}{dk} = \phi(h)\frac{du}{dh}$$

$$\therefore \quad u = \chi\left(k + \int \frac{dh}{\varphi(h)}\right) = \chi\left(k + \psi(h)\right).$$

To determine the arbitrary function χ, we observe that if $k = 0$, $u = e^{hx}$;

$$\therefore \quad \chi(\psi h) \equiv e^{hx}$$

hence if λ be determined so as to satisfy

$$\psi(\lambda) \equiv k + \psi(h)$$
$$u = \chi(\psi\lambda) = e^{\lambda x}.$$

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Hence if z be the same function of x in (6) as in (4), the operator $e^{D\phi}$ is identical with $e^{D\cdot f}$; that is

$$1 + D\phi + \frac{1}{1.2}\overline{D\phi}^2 + \&c. \equiv 1 + Df + \frac{1}{1.2}D^2f^2 + \&c. \ldots . \quad (8)$$

In order that this identity should hold, it is necessary that z, $f(x)$, $\psi(x)$ shall be three functions of x which satisfy (1) and (7), viz.

$$z = x + f(z) \ldots . \quad (7)$$
$$\psi(z) = 1 + \psi(x) \ldots . \quad (1)$$

$\phi(x)$ being put for $\frac{1}{\psi'(x)}$.

If we could then eliminate (z) from (1) and (7), any functions f, ψ, whose forms satisfy the resulting equation, will cause the identity (8) to hold.

For instance, suppose $\phi(x) = hx^2$, then $\psi x = -\frac{1}{hx}$;

hence (1)

$$x = \frac{z}{1 + hz}$$

therefore (7)
$$f(z) \equiv \frac{hz^2}{1 + hz}$$

therefore $1 + hDx^2 + \frac{h^2}{1.2}\overline{Dx^2}^2 + \&c. \equiv 1 + hD\frac{x^2}{1+hx} + \frac{h^2}{1.2}D^2\left(\frac{x^2}{1+hx}\right)^2 + \&c.$
whatever be the operand.

Again let us suppose $f(x) = hx$, then $z = \frac{x}{1-h}$;

hence (7) ψ is to be found from

$$\psi\left(\frac{x}{1-h}\right) \equiv 1 + \psi(x)$$
$$\therefore \quad \psi(x) \equiv -\frac{\log x}{\log(1-h)}$$
$$\therefore \quad \phi(x) = -x\log(1-h)$$

Thus

$$1 + hDx + \frac{h^2}{1.2}D^2x^2 + \ldots . \equiv e^{-\log(1-h)Dx} \equiv (1-h)^{-Dx}$$
$$\equiv 1 + hDx + \frac{h^2}{1.2}Dx(Dx+1) + \frac{h^3}{1.2.3}Dx(Dx+1)(Dx+2) + \ldots .$$

This is easy to verify.

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III.

On the Multiplication of the $(n-1)^{th}$ Power of a Symmetric Determinant of the n^{th} Order by the Second Power of any Determinant of the same Order.

By Thomas Muir, M. A., F. R. S. E.

1. In *Crelle's Journal*, 1853, Vol. XLIX, p. 246, § 3, Hesse gives the identity

$$\begin{vmatrix} a & b \\ b & c \end{vmatrix} \begin{vmatrix} x_1 & x_2 \\ y_1 & y_2 \end{vmatrix}^2 = \begin{vmatrix} \begin{vmatrix} a & b & x_1 \\ b & c & x_2 \\ x_1 & x_2 & 0 \end{vmatrix} & \begin{vmatrix} a & b & x_1 \\ b & c & x_2 \\ y_1 & y_2 & 0 \end{vmatrix} \\ \begin{vmatrix} a & b & x_1 \\ b & c & x_2 \\ y_1 & y_2 & 0 \end{vmatrix} & \begin{vmatrix} a & b & y_1 \\ b & c & y_2 \\ y_1 & y_2 & 0 \end{vmatrix} \end{vmatrix}$$

adding that in a subsequent part of his paper he would show of what extension the identity was capable. This he did in § 6, p. 252. Starting the process of generalisation with his mind fixed on the left-hand member, he reached the proposition that "*The product of a symmetrical determinant by the second power of any determinant of the same order is expressible as a symmetrical determinant.*" The object of the present note is to show that for the same identity there exists an extension in quite another direction, the starting point now being the *right-hand* member of it.

2. Taking the symmetric determinant of the third order

$$\begin{vmatrix} a & b & c \\ b & d & e \\ c & e & f \end{vmatrix}$$

and bordering it with pairs of the rows of the determinant $| x_1\ y_2\ z_3 |$ after the manner indicated in (1) we obtain six determinants; and making these the six distinct elements of a symmetric determinant of the third order, we have an

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...

$$\begin{vmatrix} a & b & c & x & a & b & c & x & x & y & z & 0 \\ b & d & e & x_2 & b & d & e & x_2 & x_2 & y_2 & z_2 & 0 \\ c & e & f & x_3 & c & e & f & x_3 & x_3 & y_3 & z_3 & 0 \\ x_1 & x_2 & x_3 & 0 & y & y_2 & y_3 & 0 & z_1 & z_2 & z_3 & 0 \\ a & b & c & y_1 & a & b & c & y_1 & x & y & z & 0 \\ b & d & e & y_2 & b & d & e & y_2 & x_2 & y_2 & z_2 & 0 \\ c & e & f & y_3 & c & e & f & y_3 & x_3 & y_3 & z_3 & 0 \\ x_1 & x_2 & x_3 & 0 & y & y_2 & y_3 & 0 & z_1 & z_2 & z_3 & 0 \\ a & b & c & z_1 & a & b & c & z_1 & x & y & z & 0 \\ b & d & e & z_2 & b & d & e & z_2 & x_2 & y_2 & z_2 & 0 \\ c & e & f & z_3 & c & e & f & z_3 & x_3 & y_3 & z_3 & 0 \\ x_1 & x_2 & x_3 & 0 & y_1 & y_2 & y_3 & 0 & z_1 & z_2 & z_3 & 0 \end{vmatrix} = - \begin{vmatrix} a & b & c & x_1 & x_2 & x_3 \\ b & d & e & y_1 & y_2 & y_3 \\ c & e & f & z_1 & z_2 & z_3 \end{vmatrix}^2$$

The proof is extremely simple. From one of Sylvester's theorems regarding Compound Determinants (Phil. Mag., 1851, I. p. 267) we have

$$\begin{vmatrix} a_1 b_2 c_3 d_4 & a_1 b_2 c_3 e_4 & a_1 b_2 c_3 f_4 \\ a_1 b_3 c_2 d_4 & a_1 b_3 c_2 e_4 & a_1 b_3 c_2 f_4 \\ a_2 b_3 c_1 d_4 & a_2 b_3 c_1 e_4 & a_2 b_3 c_1 f_4 \end{vmatrix} = a_1 b_2 c_3 d_4 e_5 f_6 \quad a_1 b_2 c_3 ^2.$$

Replacing in this the determinant $a_1 b_2 c_3 d_4 e_5 f_6$ by

$$\begin{matrix} a & b & c & x_1 & y_1 & z_1 \\ b & d & e & x_2 & y_2 & z_2 \\ c & e & f & x_3 & y_3 & z_3 \\ x_1 & x_2 & x_3 & 0 & 0 & 0 \\ y_1 & y_2 & y_3 & 0 & 0 & 0 \\ z_1 & z_2 & z_3 & 0 & 0 & 0 \end{matrix}$$

which is equal to $- x_1 y_2 z_3 ^2$, we at once obtain all that is required.

The form of the theorem for higher orders is apparent, and is indicated in the title of the note.

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3. It is worthy of remark that Hesse's general theorem enunciated in (1) leads directly to another of at least equal importance, viz. *Any power of a symmetrical determinant is itself expressible as a symmetrical determinant.* For, the *first* power being symmetrical, the *third* must be so also; therefore also the *fifth*, the *seventh*, &c.; and as for the *even* powers, they are known to be symmetrical in the case of any determinant. In the order of discovery, however, this theorem preceded Hesse's, being used by Sylvester in the statement of the property found by him to belong to the equation of the secular inequalities of the planets. In this connection no proof was given of it except in the *Nouvelles Annales*, the editor of which, in bringing the property referred to before his readers, prefaced the statement of the same by a few remarks on determinants. To him apparently the responsibility attaches of discovering the theorem "Le produit de déterminants symétriques est un déterminant symétrique," in order that the accustomed easy step might be made from *product* to *power*.

BEECHCROFT. BISHOPTON, SCOTLAND, *August* 1st. 1881.

IV.

On Newton's Method of Approximation.

BY F. FRANKLIN.

Let $f(x) = 0$ be an algebraic equation. Newton's method of approximation consists in adding to an approximate value, a, of a root, the correction k, $= -\frac{f(a)}{f'(a)}$; correcting the new value $a + k$, say a_1, in like manner, viz. by adding $-\frac{f(a_1)}{f'(a_1)}$; and so on. Fourier's theorem concerning this method is as follows: If between a and b there is one and only one root of the equation $f(x)=0$, and *if neither* $f'(x)$ *nor* $f''(x)$ *vanishes* between these limits, then we will be sure to approximate indefinitely to the root by Newton's method, if we begin the process at that one of the quantities a, b for which f has the same sign as f''.

The proof, as usually given, is somewhat tedious; the following proof is very brief, shows that a part of the usual statement of the theorem should be omitted, and gives immediately a measure of the rapidity of the approximation.

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Simple and Uniform Method of Obtaining Taylor's, Cayley's, and Lagrange's Series.

By J. C. Glashan, *Ottawa, Canada.*

In a short note in the *American Journal of Mathematics*, Vol. I, p. 287, I have given Taylor's Theorem under the form

$$f(x+a) = \left(1 - \int_0^a da \cdot \frac{d}{dx}\right)^{-1} fx.$$

I find that although this form is excellent as a merely symbolic notation, the operator $\left(1 - \int_0^a da \cdot \frac{d}{dx}\right)^{-1}$ introduces some obscurity in the reasoning if employed in obtaining the theorem. I therefore propose to show the real method adopted in the note and to apply it to obtain Lagrange's Series.

Taylor's Theorem. Let x and a be independent variables, and fy, $f'y$, ... $f^n y$ be continuous from $y = x$ to $y = x + a$.

Since $\frac{d}{da} f(x+a) = \frac{d}{dx} f(x+a) = f'(x+a)$,

$$\therefore \quad f(x+a) = fx + \int_0^a da f'(x+a)$$

$$= fx + \int_0^a da \left\{ f'x + \int_0^a da f''(x+a) \right\}$$

$$= fx + \frac{a}{1} f'x + \int_0^a da \int_0^a da f''(x+a)$$

$$= fx + \frac{a}{1} f'x + \frac{a^2}{2} f''x + \left(\int_0^a da\right)^3 f'''(x+a)$$

. . . . . .

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$$= fx + \frac{a}{1} f'x + \ldots\ldots + \frac{a^{n-1}}{(n-1)!} f^{n-1}x + \left(\int_0^a da\right)^n f^n(x+a)$$

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Cayley's Theorem. [illegible]

$$= \int_{a_0}^{x} f(x + a_1 + \ldots) = \int_{a_1}^{x} f(x + a_2 + \ldots) = \ldots\ldots$$

$$= \int_{a_2}^{x} f(x + a_3 + \ldots) = f(x + a_3 + \ldots)$$

$$f(x + a_1 + a_2 + \ldots) = f(x + a + a_2 + \ldots) - \int_0^{a} da_0 f'(x + a_0 + a_2 + \ldots)$$

$$= f(x + a_2 + a_3 + \ldots) - \int_0^{a_1} da_0 f'(x + a_0 + a_2 + \ldots) - \int_0^{a} da_1 \int_0^{a_1} da_0 f''(x + a_0 + a_2 + \ldots)$$

$$= f(x + a_2 + a_3 + \ldots) - \int_1^{[a]} f(x + a_2 + \ldots) - \int_2^{[a]} f(x + a_3 + \ldots)$$

$$- \int_0^{a} da_1 \int_0^{a_1} da_0 f'(x + a_0 + a_2 + \ldots)$$

$$= f(x + a_2 + a_3 + \ldots) - \int_1^{[a]} f(x + a_2 + \ldots) - \int_2^{[a]} f(x + a_3 + \ldots)$$

$$- \int_0^{a} da_1 \int_0^{a_1} da_0 \int_0^{a_0 + a_1} d(a_0 + a_1) f''(x + a_0 + a_1 + \ldots)$$

$$\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots$$

$$\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots$$

$$= f(x + a_1 + a_2 + \ldots) + \int_1^{[a]} f(x + a_2 + \ldots) + \ldots\ldots\ldots$$

$$+ \int_{n-1}^{[a]^{n-1}} f^{n-1}(x + a_n + \ldots) + \left[\int_0^{a} da\right]^{n} f^{n}(x + a_1 + a_2 + \ldots)$$

in which

$$\left[\int_0^{a} da\right]^{n} U \equiv \int_0^{a} da_0 \int_0^{a_0 + a_1} d(a_0 + a_1) \ldots \int_0^{a_1 + a_2 + \ldots + a_{n-1}} d(a_0 + a_1 + \ldots + a_{n-1}) U;$$

and $[a]^n \equiv n! \left[\int_0^{a} da\right]^{n}$ = the result of retaining only those terms of the expansion of $(a_0 + a_1 + \ldots\ldots + a_{n-1})^n$ of the form

$$C a_0^{n_0} (a_1 + a_2 + \ldots + a_s)^{n_1} (a_{s+1} + a_{s+2} + \ldots + a_{s+t})^{n_2} \ldots\ldots$$

which $\equiv$ the result of rejecting all terms of the same expansion, of the form

$$C a_0^{n_0} a_1^{n_1} a_2^{n_2} \ldots\ldots$$

in which $n_{n-1} > 1$, $n_{n-2} + n_{n-1} > 2$, $\ldots\ldots n_1 + n_2 + \ldots\ldots + n_{n-1} > n - 1$.

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Writing x for $x + a_0 + a_1 + \ldots\ldots$, the theorem becomes

$$fx = f(x-a_0) + \frac{[a]^1}{1} f'(x-a_0-a_1) + \ldots\ldots + \frac{[a]^{n-1}}{(n-1)!} f^{n-1}(x-a_0-a_1-\ldots-a_{n-1}) + R.$$

Let $\{a\}^n \equiv$ the result of retaining only those terms of the expansion of $(a_0 + a_1 + a_2 + \ldots\ldots + a_{n-1})^n$ of the form

$$Ca_0^\alpha a_\alpha^\beta a_{\alpha+\beta}^\gamma \ldots\ldots$$

and affecting each term with the sign $(-1)^{n-m}$ where $m = \frac{\alpha}{\alpha} + \frac{\beta}{\beta} + \frac{\gamma}{\gamma} + \ldots$, and the theorem may be written

$$fx = f(x-a_0) + \frac{\{a\}^1}{1} f'(x-a_1) + \ldots\ldots + \frac{\{a\}^{n-1}}{(n-1)!} f^{n-1}(x-a_{n-1}) + R.$$

At the time of the publication of the above theorem in my note entitled *An Extension of Taylor's Theorem*, (Vol. I, p. 287,) I believed it to be new, but the following note published in *Quart. Journ. Math.*, XIV., 53 (two years before mine), shows the theorem had been given long before by Professor Cayley.

"I wish to put on record the following theorem, given by me as a Senate-House Problem, January, 1851.

If $\{\alpha + \beta + \gamma \ldots\}^p$ denote the expansion of $(\alpha + \beta + \gamma \ldots)^p$, retaining those terms $N\alpha^a\beta^b\gamma^c \ldots$ only in which

$$b + c + d \ldots \not> p-1,\ c + d \ldots \not> p-2,\ \&c.,\ \&c.,$$

then

$$x^n = (x+\alpha)^n - n\{\alpha\}^1(x+\alpha+\beta)^{n-1} + \frac{1}{2}n(n-1)\{\alpha+\beta\}^2(x+\alpha+\beta+\gamma)^{n-2}$$
$$- \frac{1}{6}n(n-1)(n-2)\{\alpha+\beta+\gamma\}^3(x+\alpha+\beta+\gamma+\delta)^{n-3} + \&c.$$

The theorem, in a somewhat different and imperfectly stated form, is given, Burg, *Crelle*, t. I. (1826), p. 368, as a generalization of Abel's theorem

$$(x+\alpha)^n = x^n + n\alpha(x+\beta)^{n-1} + \frac{1}{2}n(n-1)\alpha(\alpha-2\beta)(x+2\beta)^{n-2}$$
$$+ \frac{1}{6}n(n-1)(n-2)\alpha(\alpha-3\beta)^2(x+3\beta)^{n-3} + \&c."$$

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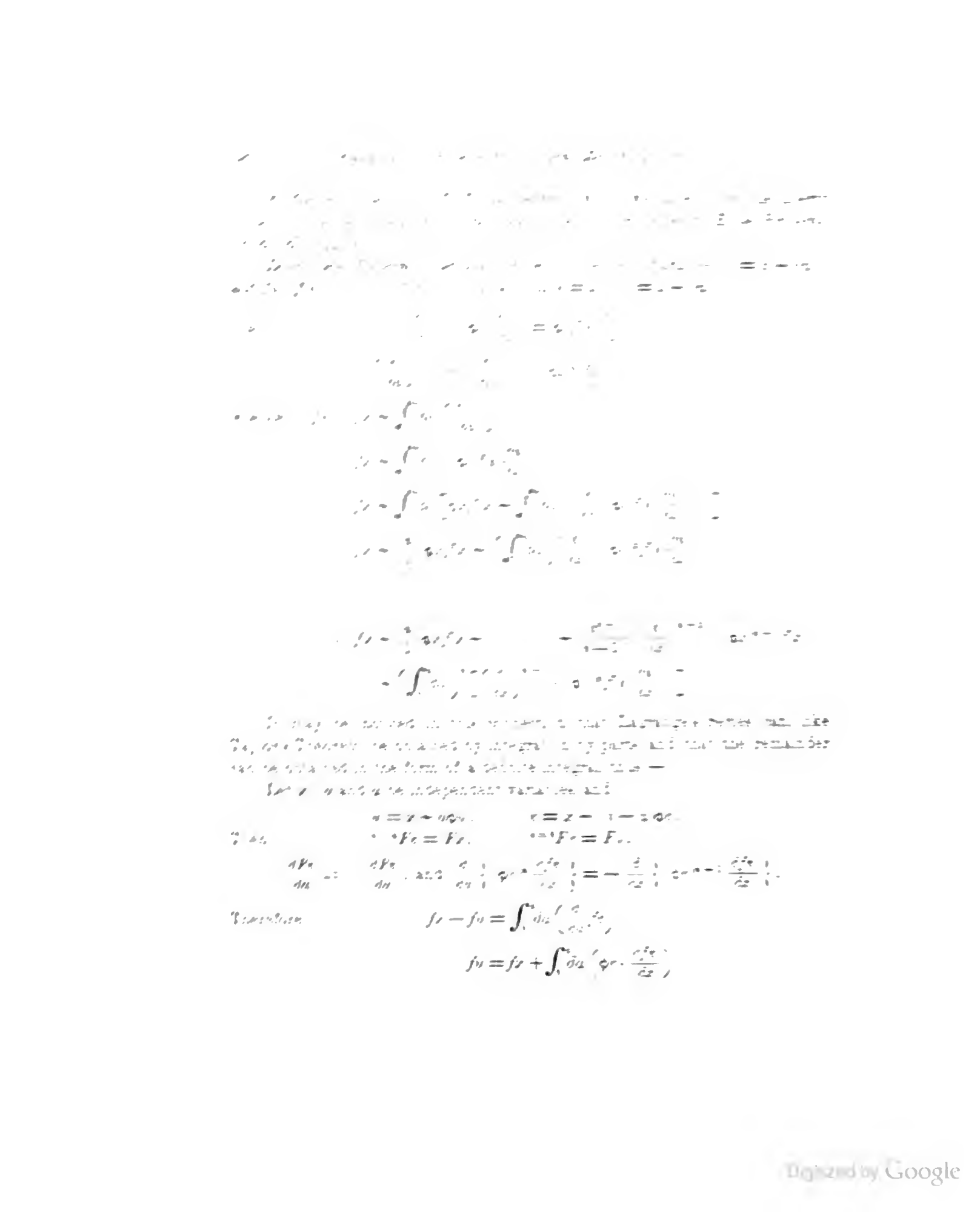

Integrating by parts,

$$\int_0^a da\left(\phi v \cdot \frac{dfv}{dx}\right) = a\phi x \,.\, f'x - \int_0^a da \left\{ a \frac{d}{da}\left(\phi v \cdot \frac{dfv}{dx}\right)\right\}$$
$$= a\phi x \,.\, f'x + \frac{1}{2}\int_0^a da\left[\frac{d(a^2)}{da} \cdot \frac{d}{dx}\left\{(\phi v)^2 \frac{dfv}{dx}\right\}\right].$$

Similarly

$$\frac{1}{2}\int_0^a da\left[\frac{d(a^2)}{da} \cdot \frac{d}{dx}\left\{(\phi v)^2 \frac{dfv}{dx}\right\}\right] = \frac{a^2}{2}\frac{d}{dx}\left\{(\phi x)^2 f'x\right\}$$
$$+ \frac{1}{2\,.\,3}\int_0^a da\left[\frac{d(a^3)}{da}\left(\frac{d}{dx}\right)^2\left\{(\phi v)^3 \frac{dfv}{dx}\right\}\right];$$

. . . . . .

. . . . . .

$$\frac{1}{n!}\int_0^a da\left[\frac{d(a^n)}{da}\left(\frac{d}{dx}\right)^{n-1}\left\{(\phi v)^n \frac{dfv}{dx}\right\}\right] =$$
$$\frac{a^n}{n!}\left(\frac{d}{dx}\right)^{n-1}\left\{(\phi x)^n f'x\right\} + \frac{1}{n!}\int_0^a da\left[a^n\left(\frac{d}{dx}\right)^n\left\{(\phi v)^{n+1}\frac{dfv}{dx}\right\}\right].$$

$$\therefore \quad fu = fx + \frac{a}{1}\phi x \,.\, f'x + \frac{a}{2}\frac{d}{dx}\left\{(\phi x)^2 f'x\right\} + \ldots\ldots\ldots$$
$$+ \frac{a^n}{n!}\left(\frac{d}{dx}\right)^{n-1}\left\{(\phi x)^n f'x\right\} + \frac{1}{n!}\int_0^a da\left[a^n\left(\frac{d}{dx}\right)^n\left\{(\phi v)^{n+1}\frac{dfv}{dx}\right\}\right].$$

This form of the remainder corresponds to that of Taylor's Theorem obtained by integration by parts. (See also xx_1 of the article following this, entitled *Forms of Rolle's Theorem.*) This form can easily be reduced to that obtained by Zolotareff's method, (*Williamson's Integral Calculus*, 3d edition, p. 159), thus:

$$\int_0^a da\left[a^n\left(\frac{d}{dx}\right)^n\left\{(\phi v)^{n+1}\frac{dfv}{dx}\right\}\right] = \left(\frac{d}{dx}\right)^n \int_0^a da\left\{(a\,.\,\phi v)^n \phi v f'v \frac{dv}{dx}\right\}$$
$$= \left(\frac{d}{dx}\right)^n \int_a^v da\left\{(a\,.\,\phi v + x - v)^n f'v \frac{dv}{da}\right\}$$
$$= \left(\frac{d}{dx}\right)^n \int_x^v dv\left\{(a\,.\,\phi v + x - v)^n f'v\right\}.$$

P. S.—I find that a form for the remainder in Lagrange's Series was given by Schlömilch, *Liouville*, III_2, 390, (1858.)

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Forms of Euler's Theorem.

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$$[illegible] \equiv [illegible]$$

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If u be a complex variable,

$\mathfrak{S}fu \equiv$ the protensive (real) part of fu;

$\mathfrak{V}fu \equiv$ the ditensive (imaginary) part of fu.

I. Functions of a Simple Variable.

1. *Fundamental Form.* (*Rolle's.*) Let Fx and $F'x$ be continuous from $x = a$ to $x = b$, and $Fb - Fa = 0$; then will

$$F'\mu = 0. \qquad \text{i.}$$

A proof of this theorem is given in nearly every text-book on the differential calculus; perhaps the best is that by Professor Mansion in his *Leçons d'Analyse infinitésimale*, (*Gand*).

2. *Extension of Rolle's Form.* If fx, ϕx and $f'x : \phi'x$ be continuous from $x = a$ to $x = b$, and $fb - fa = 0$, then will

$$f'\mu : \phi'\mu = 0. \qquad \text{ii.}$$

This form may be proved by reasoning similar to that employed to prove the Fundamental Form, or it may be deduced from the latter thus:

Let $fx = F\phi x$ and $\mu_1 \equiv \phi a + \theta(\phi b - \phi a)$; then, since fx and ϕx are both continuous from $x = a$ to $x = b$, $F\phi x$ will remain continuous while ϕx varies *continuously* from ϕa to ϕb, also $D_{\phi x} F\phi x = D_x F\phi x : D_x \phi x = f'x : \phi'x$ is continuous between the same limits.

Therefore by i. $$D_{\mu_1} F\mu_1 = 0 \qquad (\alpha).$$

But since ϕx is continuous from $x = a$ to $x = b$, although it need not always be intermediate between ϕa and ϕb, yet it must be capable of assuming any proposed intermediate value for at least one value of x between a and b, *i. e.* $\mu_1 = \phi\mu$.

Hence $D_{\mu_1} F\mu_1 = D_{\phi\mu} F\phi\mu = D_\mu F\phi\mu : D_\mu \phi\mu = f'\mu : \phi'\mu$, $= 0$ by (α).

3. *Lagrange's Form.* Let $F_1 x$ and $F_1' x$ be continuous from $x = a$ to $x = b$, then will

$$F_1 b - F_1 a = (b - a) F_1'\mu. \qquad \text{iii.}$$

Let $$Fx \equiv \frac{F_1 x}{F_1 b - F_1 a} - \frac{x}{b - a},$$

then $$F'\mu \equiv \frac{F_1'\mu}{F_1 b - F_1 a} - \frac{1}{b - a} = 0, \text{ by i.};$$

hence $$F_1 b - F_1 a = (b - a) F_1'\mu.$$

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6. *Extension of Cauchy's Form.* Let f_1x, $f_1'x$, f_2x, $f_2'x$, ... f_nx, $f_n'x$, ϕ_1x, $\phi_1'x$, ϕ_2x, $\phi_2'x$, ... ϕ_nx, ϕ'_nx be all continuous from $x=a$ to $x=b$, then will

$$\frac{f'_1\mu}{f_1b-f_1a}+\frac{f'_2\mu}{f_2b-f_2a}+\ldots\ldots+\frac{f'_n\mu}{f_nb-f_na}$$
$$-\left\{\frac{\varphi'_1\mu}{\varphi_1b-\varphi_1a}+\frac{\varphi'_2\mu}{\varphi_2b-\varphi_2a}+\ldots\ldots+\frac{\varphi'_n\mu}{\varphi_nb-\varphi_na}\right\}=0. \qquad \text{vi.}$$

Let $$Fx\equiv\frac{f_1x}{f_1b-f_1a}+\frac{f_2x}{f_2b-f_2a}+\ldots\ldots+\frac{f_nx}{f_nb-f_na}$$
$$-\left\{\frac{\varphi_1x}{\varphi_1b-\varphi_1a}+\frac{\varphi_2x}{\varphi_2b-\varphi_2a}+\ldots\ldots+\frac{\varphi_nx}{\varphi_nb-\varphi_na}\right\},$$

then i. becomes vi.

Cor. If $fx=f_1x=f_2x=\ldots\ldots=f_nx$, then will

$$fb-fa=nf'\mu:\left\{\frac{\varphi'_1\mu}{\varphi_1b-\varphi_1a}+\ldots\ldots+\frac{\varphi'_n\mu}{\varphi_nb-\varphi_na}\right\}. \qquad \text{vii.}$$

Fx being continuous, n must in general be finite.

7. *Forms expressed by Definite Integrals.* Let fx, ϕx, ψx, $\int_c^x fx.\phi x dx$ and $\int_c^x fx.\psi x dx$ be continuous from $x=a$ to $x=b$, and $fx\neq 0$ and $\psi x\neq 0$, then will

$$\int_a^b fx.\phi x dx=\frac{\varphi\mu}{\psi\mu}\int_a^b fx.\psi x dx. \qquad \text{viii.}$$

Let $$Fx\equiv\frac{\int_c^x fx.\phi x dx}{\int_a^b fx.\phi x dx}-\frac{\int_c^x fx.\psi x dx}{\int_a^b fx.\psi x dx};$$

then $$F'\mu\equiv\frac{f\mu.\phi\mu}{\int_a^b fx.\phi x dx}-\frac{f\mu.\psi\mu}{\int_a^b fx.\psi x dx}=0 \text{ by i.}$$

consequently $$\int_a^b fx.\phi x dx=\frac{\varphi\mu}{\psi\mu}\int_a^b fx.\psi x dx.$$

Cor. If $\psi x=1$, then will

$$\int_a^b fx.\phi x dx=\phi\mu\int_a^b fx dx. \qquad \text{ix.}$$

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The usual proofs of viii. and ix. are substantially the same as Moigno's proof of Cauchy's Theorem, but no hint is at the same time given that iii. and viii. differ only in form of statement. xi., for the case $c = b$, was given by A. Winckler in *Sitzungsberichte der math.-nat. Klasse*, Wien, LX, (1869). (γ) was given by Grunert in *Grunert's Archiv.*, IV, 113. (β) was given by U. H. Meyer in *Grunert's Archiv.*, V, 216. xiv., xiv_1, and xiv_2 were given by Hankel in *Schlömilch's Zeitschrift*, XIV, (1869).

8. *Remainder in Taylor's Theorem.* In the Special Case of Cauchy's Form, let $g = l = b$, $\lambda = a$, $e = o$, $\varepsilon = c - a$, $\eta = k + b$ and $b = a + h$, then v. becomes

$$f(a+h) - \left\{ fa + \frac{h}{1} f'a + \ldots\ldots + \frac{h^n}{n!} f^n a \right\}$$

$$= \left[\phi(c+h) - \left\{ \phi c + \frac{h}{1}\phi' c + \ldots\ldots + \frac{h^p}{p!}\phi^p c \right\} \right.$$

$$\left. + \psi(k+h) - \left\{ \psi k + \frac{h}{1}\psi' k + \ldots\ldots + \frac{h^q}{q!}\psi^q k \right\} \right]$$

$$\times \frac{p!\,q!\,(1-\theta)^n h^n f^{n+1}(a+\theta h)}{n!\,[q!\,(1-\theta)^p h^p \varphi^{p+1}(c+\theta h) + p!\,\theta^q h^q \psi^{q+1}\{k+(1-\theta)h\}]} \equiv R. \qquad \text{xv.}$$

R gives at once all the forms, exclusive of those involving definite integrals, hitherto proposed for the remainder in Taylor's Theorem for a simple variable. Thus, if ψx be constant and $c = a$, R will become the *general* form given in the *Mémoires de l'Académie . . . . . de Montpellier*, V. (1861–1863), and if in addition $p = 0$, R will become the *special* form given in the same memoir. (*Todhunter's Dif. Calc.*, 6th *edition*, pp. 404–406). The latter form is also given by Schlömilch in his *Uebungsbuch*, p. 202. If $p = n$, R will become the form given by Professor Mansion in *Messenger of Math.*, V_2, 161.

If ϕx be constant, R will become a form of which the special case for $k = q = 0$ was given by Schlömilch in *Liouville's Journal*, III_2, 384, (1858); also in his *Handbuch*, 1847. The forms of Roche (1858), Cauchy, and Lagrange (1807) are all particular cases of this form of Schlömilch's.

Definite-integral forms of the remainder can be reduced by viii. or ix. above. Thus, to obtain Roche's form in expanding $f(x+h)$ by integration by parts, let the remainder

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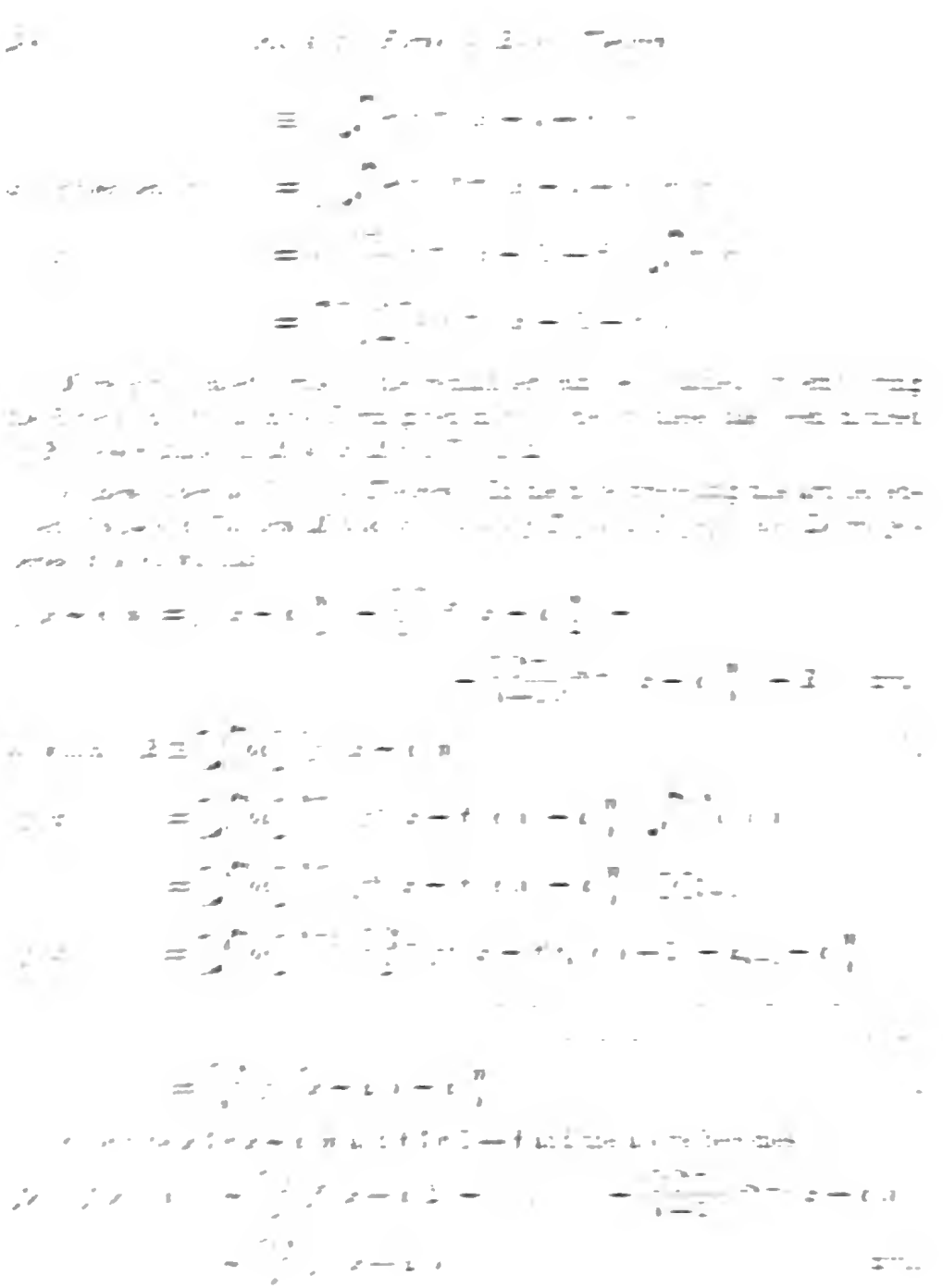

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In III. of *An Extension of Taylor's Theorem*, (this Journal, Vol. I, p. 287), the remainder

$$\equiv\left[\int_0^a da\right]^{:n}\left\{1-\int_0^{a;n+1} d(a;n+1).\frac{d}{dx}\right\}^{-1} f^n\left(x+a;\frac{m}{n+1}\right)$$

and by I. of the same note, this

$$\equiv\left[\int_0^a da\right]^{:n} f^n(x+a;m)$$

which is (δ) given above.

10. *Remainder in Lagrange's Series.* Let x and y be independent variables, $w=x+y\phi w$, $v=x+a\phi v$, $u=x+b\phi u$ and $u_1=x+\mu\phi u_1$; also let fw, $\frac{dfw}{dy}$, ... $\frac{d^{n+1}w}{dy^{n+1}}$, $\psi(c-y)$, $\psi'(c-y)$ be all continuous from $y=a$ to $y=b$, and $\psi'(c-\mu)\neq 0$.

Since $$\frac{d}{dy}\left\{(\phi w)^n\frac{dfw}{dx}\right\}=\frac{d}{dx}\left\{(\phi w)^{n+1}\frac{dfw}{dx}\right\},$$

if $$Fy\equiv fw+\frac{k-y}{1}\phi w\frac{dfw}{dx}+\ldots\ldots+\frac{(k-y)^n}{n!}\left(\frac{d}{dx}\right)^{n-1}\left\{(\phi w)^n\frac{dfw}{dx}\right\},$$

then $$F'y\equiv\frac{(k-y)^n}{n!}\left(\frac{d}{dx}\right)^n\left\{(\phi w)^{n+1}\frac{dfw}{dx}\right\},$$

and, by iv., $$Fb=Fa+\frac{\psi(c-a)-\psi(c-b)}{\psi'(c-\mu)}F'\mu;$$

or, writing this in full,

$$fu+\frac{k-b}{1}\phi u\frac{dfu}{dx}+\ldots\ldots+\frac{(k-b)^n}{n!}\left(\frac{d}{dx}\right)^{n-1}\left\{(\phi u)^n\frac{dfu}{dx}\right\}=$$
$$fv+\frac{k-a}{1}\phi v\frac{dfv}{dx}+\ldots\ldots+\frac{(k-a)^n}{n!}\left(\frac{d}{dx}\right)^{n-1}\left\{(\phi v)^n\frac{dfv}{dx}\right\}$$
$$+\frac{\psi(c-a)-\psi(c-b)}{\psi'(c-\mu)}\cdot\frac{(k-\mu)^n}{n!}\left(\frac{d}{dx}\right)^n\left\{(\phi u_1)^{n+1}\frac{dfu_1}{dx}\right\}. \qquad \text{xviii.}$$

If $k=b$, $c=b+h$ and $a=0$ and therefore $v=x$ and $u_1=x+\theta b\phi u_1$, this reduces to Lagrange's Series, or

$$fu=fx+\frac{b}{1}\phi x.f'x+\ldots\ldots\ldots+\frac{b^n}{n!}\left(\frac{d}{dx}\right)^{n-1}\{(\phi x)^n f'x\}$$
$$+\frac{\psi(h+b)-\psi h}{\psi'\{h+(1-\theta)b\}}\cdot\frac{\{(1-\theta)b\}^n}{n!}\left(\frac{d}{dx}\right)^n\left\{(\phi u_1)^{n+1}\frac{dfu_1}{dx}\right\}. \qquad \text{xix.}$$

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Let $h = 0$ and $\psi h = h^{p+1}$, then the remainder will become

$$\frac{(1-\theta)^{n-p} h^{n+1}}{n!\,(p+1)} \left(\frac{d}{dx}\right)^n \left\{ (\varphi u_1)^{n+1} \frac{df u_1}{dx} \right\}. \qquad \text{xx.}$$

For $\psi(c-y)$ write $\psi_1(y+h)$, which may be done since ψ and ψ_1 are both arbitrary, then making $k = h$ and $a = 0$, xviii. becomes

$$fu = fx + \ldots + \frac{\psi_1(c+h) - \psi_1 c}{\psi'_1(c+\theta h)} \cdot \frac{(1-\theta)^n h^n}{n!} \left(\frac{d}{dx}\right)^n \left\{ (\varphi u_1)^{n+1} \frac{df u_1}{dx} \right\}. \qquad \text{xxi.}$$

Again for $\psi(c-y)$ and $\psi_1(y+h)$, there may be substituted functions of the form of W_x, V_x, or $V_x - W_x$ of 5, or functions bearing the same relation to Lagrange's Series that these do to Taylor's.

In the note *Simple and Uniform Method*, &c., it is shown that if $u = x + h\varphi u$ and $v = x + (h-\beta)\varphi x$ the remainder in Lagrange's Series is

$$\frac{1}{n!}\int_0^\theta d\beta \left[\beta^n \left(\frac{d}{dx}\right)^n \left\{ (\varphi x)^{n+1} \frac{df v}{dx} \right\} \right]$$

which

$$= \frac{1}{n!}\int_0^\theta d\beta \left[\beta^{n-p} \left(\frac{d}{dx}\right)^n \left\{ (\varphi x)^{n+1} \frac{df v}{dx} \right\} \beta^p \right]$$

by ix.

$$= \frac{(1-\theta)^{n-p} h^{n+1}}{n!\,(p+1)} \left(\frac{d}{dx}\right)^n \left\{ (\varphi u_1)^{n+1} \frac{df u_1}{dx} \right\} \qquad \text{xx}_1.$$

in which $u_1 = x + \theta h \varphi u_1$. This is the same form of remainder as that found in xx. Had viii. been used instead of ix. in the reduction, forms like those of xix. or xxi. would have been obtained.

II. Functions of a Complex Variable.

11. *General Form.* Let $u = x + i\varphi x$, $u_0 = x_0 + i\varphi x_0$, $u_1 = x_1 + i\varphi x_1$, $v_1 = u_0 + \theta_1(u_1 - u_0)$, and $v_2 = u_0 + \theta_2(u_1 - u_0)$. If ϕx and $\phi' x$ remain continuous while x varies continuously from $x = x_0$ to $x = x_1$, if also Φu and $\Phi' u$ remain continuous from $u = u_0$ to $u = u_1$, and if $\Phi u_1 - \Phi u_0 = 0$, then will

$$\mathfrak{S}\Phi' v_1 = 0 \quad \text{and} \quad \mathfrak{V}\Phi' v_2 = 0. \qquad \text{xxii.}$$

12. *Special Form.* Let $w = (u - u_0) : (u_1 - u_0)$ and

$$\Phi u \equiv (u_1 - u_0)\{(Fu_1 - Fu_0)(\Psi w - \Psi 0) - (Fu - Fu_0)(\Psi 1 - \Psi 0)\}$$

and $\therefore \Phi' u \equiv (Fu_1 - Fu_0)\Psi' w - (u_1 - u_0)(\Psi 1 - \Psi 0) F' u$

$$\therefore Fu_1 - Fu_0 = \frac{\Psi_1 1 - \Psi_1 0}{\Psi'_1 \theta_1} \mathfrak{S}\{(u_1 - u_0) F' v_1\} + \frac{\Psi_2 1 - \Psi_2 0}{\Psi'_2 \theta_2} \mathfrak{V}\{(u_1 - u_0) F' v_2\}. \qquad \text{xxiii.}$$

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13. *Remainder in Taylor's Theorem.* In the preceding form let

$$Fu \equiv f(h+lu) + \frac{k-lu}{1} f'(h+lu) + \ldots\ldots\ldots + \frac{(k-lu)^n}{n!} f^n(h+lu),$$

$$\Psi w \equiv \psi(a+bw) + \frac{c-bw}{1} \psi'(a+bw) + \ldots\ldots\ldots + \frac{(c-bw)^m}{m!} \psi^m(a+bw),$$

$$\therefore f(h+lu_1) + \frac{k-lu_1}{1} f'(h+lu_1) + \ldots\ldots\ldots + \frac{(k-lu_1)^n}{n!} f^n(h+lu_1)$$

$$- \left\{ f(h+lu_0) + \frac{k-lu_0}{1} f'(h+lu_0) + \ldots\ldots\ldots + \frac{(k-lu_0)^n}{n!} f^n(h+lu_0) \right\}$$

$$= \left[\psi_1(a+b) + \frac{c-b}{1} \psi_1'(a+b) + \ldots\ldots\ldots + \frac{(c-b)^p}{p!} \psi_1^p(a+b) \right.$$

$$\left. - \left\{ \psi_1 a + \frac{c}{1} \psi_1' a + \ldots\ldots\ldots + \frac{c^p}{p!} \psi_1^p a \right\} \right] R_1$$

$$+ \left[\psi_2(\alpha+\beta) + \frac{\gamma-\beta}{1} \psi_2'(\alpha+\beta) + \ldots\ldots\ldots + \frac{(\gamma-\beta)^q}{q!} \psi_2^q(\alpha+\beta) \right.$$

$$\left. - \left\{ \psi_2 \alpha + \frac{\gamma}{1} \psi_2' \alpha + \ldots\ldots\ldots + \frac{\gamma^q}{q!} \psi_2^q \alpha \right\} \right] R_2 \equiv R. \qquad \text{xxiv.}$$

in which $$R_1 \equiv \frac{p!\, l\, \mathfrak{S}\{(u_1-u_0)(k-lv_1)^n f^{n+1}(h+lv_1)\}}{n!\, b\, (c-\theta_1 b)^p \psi_1^{p+1}(a+\theta_1 b)}, \qquad (\zeta_1).$$

and $$R_2 \equiv \frac{q!\, l\, \mathfrak{V}\{(u_1-u_0)(k-lv_2)^n f^{n+1}(h+lv_2)\}}{n!\, \beta\, (\gamma-\theta_2\beta)^q \psi_2^{q+1}(\alpha+\theta_2\beta)}. \qquad (\zeta_2).$$

Had it been assumed that

$$\Psi w \equiv \Psi_1(a_1+b_1 w) - \Psi_2(a_2-b_2 w) + \frac{c_1-b_1 w}{1} \Psi_1'(a_1+b_1 w) - \frac{c_2-b_2 w}{1} \Psi_2(a_2-b_2 w) + \&c.,$$

a general theorem would have been obtained of which v. is the form for a real variable in the particular case $l = b_1 = 1$.

Taylor's theorem with Remainder is the particular case of xxiv. for $h = 0$, $k = u_1$, and $l = 1$. If in addition to these limitations, $c = b$, $\gamma = \beta$, and $u_1 - u_0 = t$, xxiv. becomes (writing u for u_0)

$$f(u+t) - \left\{ fu + \frac{t}{1} f'u + \ldots\ldots\ldots + \frac{t^n}{n!} f^n u \right\}$$

$$= \left[\psi_1(a+b) - \left\{ \psi_1 a + \frac{b}{1} \psi_1' a + \ldots\ldots\ldots + \frac{b^p}{p!} \psi_1^p a \right\} \right] R_1$$

$$+ \left[\psi_2(\alpha+\beta) - \left\{ \psi_2 \alpha + \frac{\beta}{1} \psi_2' + \alpha \ldots\ldots\ldots + \frac{\beta^q}{q!} \psi_2^q \alpha \right\} \right] R_2 \qquad \text{xxv.}$$

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On the 8-Square Imaginaries.

By Professor Cayley.

I write throughout 0 to denote positive unity, and uniting with it the seven imaginaries $1, \ldots 7$, form an octavic system $0, 1, 2, 3, 4, 5, 6, 7$, the laws of combination being

$$0^2 = 0,\ 1^2 = 2^2 = 3^2 = 4^2 = 5^2 = 6^2 = 7^2 = -0,$$

$$\begin{array}{lll} 123 = \varepsilon_1, & 145 = \varepsilon_2, & 167 = \varepsilon_3, \\ & 246 = \varepsilon_4, & 257 = \varepsilon_5, \\ & 347 = \varepsilon_6, & 356 = \varepsilon_7, \end{array}$$

where $\varepsilon = \pm$, viz. each ε has a determinate value $+$ or $-$ as the case may be; and where the formula, $123 = \varepsilon_1$, denotes the six equations

$$\begin{array}{lll} 23 = \varepsilon_1 1, & 31 = \varepsilon_1 2, & 12 = \varepsilon_1 3, \\ 32 = -\varepsilon_1 1, & 13 = -\varepsilon_1 2, & 21 = -\varepsilon_1 3, \end{array}$$

and so for the other formulæ: the multiplication table of the eight symbols thus is

	0	1	2	3	4	5	6	7
0	0	1	2	3	4	5	6	7
1	1	-0	$\varepsilon_1 3$	$-\varepsilon_1 2$	$\varepsilon_2 5$	$-\varepsilon_2 4$	$\varepsilon_3 7$	$-\varepsilon_3 6$
2	2	$-\varepsilon_1 3$	-0	$\varepsilon_1 1$	$\varepsilon_4 6$	$\varepsilon_5 7$	$-\varepsilon_4 4$	$-\varepsilon_5 5$
3	3	$\varepsilon_1 2$	$-\varepsilon_1 1$	-0	$\varepsilon_6 7$	$\varepsilon_7 6$	$-\varepsilon_7 5$	$-\varepsilon_6 4$
4	4	$-\varepsilon_2 5$	$-\varepsilon_4 6$	$-\varepsilon_6 7$	-0	$\varepsilon_2 1$	$\varepsilon_4 2$	$\varepsilon_6 3$
5	5	$\varepsilon_2 4$	$-\varepsilon_5 7$	$-\varepsilon_7 6$	$-\varepsilon_2 1$	-0	$\varepsilon_7 3$	$\varepsilon_5 2$
6	6	$-\varepsilon_3 7$	$\varepsilon_4 4$	$\varepsilon_7 5$	$-\varepsilon_4 2$	$-\varepsilon_7 3$	-0	$\varepsilon_3 1$
7	7	$\varepsilon_3 6$	$\varepsilon_5 5$	$\varepsilon_6 4$	$-\varepsilon_6 3$	$-\varepsilon_5 2$	$-\varepsilon_3 1$	-0

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$$Z_1 = -12$$

$$22\ 45 \cdot 24\ 53 \cdot 25\ 34 =$$

$$\begin{aligned}
1,2_3 &= -1,3_2 = \quad 2,3_1 \\
1,2_3 &= -2,3_1 = \quad 1,3_2 \\
1,2_4 &= -1,3_4 = -2,3_4 \\
1,3_4 &= \quad 1,2_4 = \quad 2,3_4 \\
1,4_5 &= \quad 2,4_5 = -3,4_5 \\
1,2_5 &= -1,3_5 = \quad 2,3_5 \\
1,3_5 &= -1,2_5 = \quad 2,3_5
\end{aligned}$$

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We may without loss of generality assume $\varepsilon_1 = \varepsilon_2 = \varepsilon_3 = +$; the equations then become

$$\begin{aligned}
+ &= -\varepsilon_4\varepsilon_7 = \quad \varepsilon_5\varepsilon_6 \\
+ &= -\varepsilon_4\varepsilon_5 = \quad \varepsilon_6\varepsilon_7 \\
+ &= -\varepsilon_4\varepsilon_6 = \quad \varepsilon_5\varepsilon_7 \\
\varepsilon_4 &= -\varepsilon_6 \;\; = -\varepsilon_7 \\
\varepsilon_5 &= \quad \varepsilon_7 \;\; = \quad \varepsilon_6 \\
\varepsilon_6 &= \quad \varepsilon_5 \;\; = -\varepsilon_4 \\
\varepsilon_7 &= -\varepsilon_4 \;\; = \quad \varepsilon_5
\end{aligned}$$

and writing $\theta = \pm$ at pleasure, these are all satisfied if $-\varepsilon_4 = \varepsilon_5 = \varepsilon_6 = \varepsilon_7 = \theta$. The terms written down all disappear, and the sum of the squares of the eight coefficients thus becomes equal to the product of two sums each of them of eight squares, viz., this is the case if $\varepsilon_1 = \varepsilon_2 = \varepsilon_3 = +$, $-\varepsilon_4 = \varepsilon_5 = \varepsilon_6 = \varepsilon_7 = \theta$, θ being $= \pm$ at pleasure: the resulting system of imaginaries may be said to be an 8-square system.

We may inquire whether the system is associative; for this purpose, supposing in the first instance that the ε's remain arbitrary, we form the complete system of the values of the triplets $12{\cdot}3$, $1{\cdot}23$, etc. (read the top line $12{\cdot}3 = -\varepsilon_1 0$, $1{\cdot}23 = -\varepsilon_1 0$, the next line $12{\cdot}4 = \varepsilon_1\varepsilon_5 7$, $1{\cdot}24 = \varepsilon_3\varepsilon_4 7$, and so in other cases):

$12{\cdot}3 =$	$1{\cdot}23 =$	$-\varepsilon_1$	$-\varepsilon_1$	0
$12{\cdot}4 =$	$1{\cdot}24 =$	$\varepsilon_1\varepsilon_6$	$\varepsilon_3\varepsilon_4$	7
$12{\cdot}5 =$	$1{\cdot}25 =$	$\varepsilon_1\varepsilon_7$	$-\varepsilon_3\varepsilon_5$	6
$12{\cdot}6 =$	$1{\cdot}26 =$	$-\varepsilon_1\varepsilon_7$	$-\varepsilon_3\varepsilon_4$	5
$12{\cdot}7 =$	$1{\cdot}27 =$	$-\varepsilon_1\varepsilon_6$	$\varepsilon_3\varepsilon_5$	4
$13{\cdot}4 =$	$1{\cdot}34 =$	$-\varepsilon_1\varepsilon_4$	$-\varepsilon_3\varepsilon_6$	6
$13{\cdot}5 =$	$1{\cdot}35 =$	$-\varepsilon_1\varepsilon_5$	$\varepsilon_3\varepsilon_7$	7
$13{\cdot}6 =$	$1{\cdot}36 =$	$\varepsilon_1\varepsilon_4$	$\varepsilon_3\varepsilon_7$	4
$13{\cdot}7 =$	$1{\cdot}37 =$	$\varepsilon_1\varepsilon_5$	$-\varepsilon_3\varepsilon_6$	5
$14{\cdot}5 =$	$1{\cdot}45 =$	$-\varepsilon_2$	$-\varepsilon_5$	0
$14{\cdot}6 =$	$1{\cdot}46 =$	$\varepsilon_2\varepsilon_7$	$\varepsilon_1\varepsilon_4$	3
$14{\cdot}7 =$	$1{\cdot}47 =$	$\varepsilon_2\varepsilon_5$	$-\varepsilon_1\varepsilon_6$	2
$15{\cdot}6 =$	$1{\cdot}56 =$	$-\varepsilon_2\varepsilon_4$	$-\varepsilon_1\varepsilon_7$	2
$15{\cdot}7 =$	$1{\cdot}57 =$	$-\varepsilon_2\varepsilon_5$	$\varepsilon_1\varepsilon_5$	3
$16{\cdot}7 =$	$1{\cdot}67 =$	$-\varepsilon_3$	$-\varepsilon_3$	0
$23{\cdot}4 =$	$2{\cdot}34 =$	$\varepsilon_1\varepsilon_6$	$-\varepsilon_5\varepsilon_6$	5
$23{\cdot}5 =$	$2{\cdot}35 =$	$-\varepsilon_1\varepsilon_3$	$-\varepsilon_4\varepsilon_7$	4
$23{\cdot}6 =$	$2{\cdot}36 =$	$\varepsilon_1\varepsilon_3$	$-\varepsilon_5\varepsilon_7$	7
$23{\cdot}7 =$	$2{\cdot}37 =$	$-\varepsilon_1\varepsilon_3$	$-\varepsilon_4\varepsilon_6$	6
$24{\cdot}5 =$	$2{\cdot}45 =$	$-\varepsilon_4\varepsilon_7$	$-\varepsilon_1\varepsilon_3$	3
$24{\cdot}6 =$	$2{\cdot}46 =$	$-\varepsilon_4$	$-\varepsilon_4$	0
$24{\cdot}7 =$	$2{\cdot}47 =$	$\varepsilon_3\varepsilon_4$	$\varepsilon_1\varepsilon_6$	1
$25{\cdot}6 =$	$2{\cdot}56 =$	$-\varepsilon_3\varepsilon_5$	$\varepsilon_1\varepsilon_7$	1
$25{\cdot}7 =$	$2{\cdot}57 =$	$-\varepsilon_5$	$-\varepsilon_5$	0
$26{\cdot}7 =$	$2{\cdot}67 =$	$-\varepsilon_4\varepsilon_5$	$-\varepsilon_1\varepsilon_5$	3
$34{\cdot}5 =$	$3{\cdot}45 =$	$-\varepsilon_3\varepsilon_6$	$\varepsilon_1\varepsilon_2$	2
$34{\cdot}6 =$	$3{\cdot}46 =$	$-\varepsilon_3\varepsilon_5$	$-\varepsilon_1\varepsilon_4$	1
$34{\cdot}7 =$	$3{\cdot}47 =$	$-\varepsilon_5$	$-\varepsilon_6$	0
$35{\cdot}6 =$	$3{\cdot}56 =$	$-\varepsilon_7$	$-\varepsilon_7$	0
$35{\cdot}7 =$	$3{\cdot}57 =$	$\varepsilon_3\varepsilon_7$	$-\varepsilon_1\varepsilon_5$	1
$36{\cdot}7 =$	$3{\cdot}67 =$	$-\varepsilon_5\varepsilon_7$	$\varepsilon_1\varepsilon_3$	2
$45{\cdot}6 =$	$4{\cdot}56 =$	$\varepsilon_2\varepsilon_3$	$-\varepsilon_6\varepsilon_7$	7
$45{\cdot}7 =$	$4{\cdot}57 =$	$-\varepsilon_2\varepsilon_3$	$-\varepsilon_4\varepsilon_5$	6
$46{\cdot}7 =$	$4{\cdot}67 =$	$-\varepsilon_4\varepsilon_5$	$-\varepsilon_2\varepsilon_3$	5
$56{\cdot}7 =$	$5{\cdot}67 =$	$-\varepsilon_6\varepsilon_7$	$\varepsilon_2\varepsilon_5$	4

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Write as before $a = a_1 = a_2 = -1$, then disregarding the lines each as the first line which are the symbols ζ and writing down only the signs as given in the first and fourth columns, these are

a_4 a_6	a_5 $-a_7$	$-$ $-a_3a_6$	$-a_3$ $-a_6$
a_5 $-a_7$	a_4 a_6	$-$ $-a_3a_7$	a_4 $-a_6$
$-a_4$ $-a_6$	a_7 $-a_5$	$-a_3a_4$ $-$	$-a_3a_5$ $-$
$-a_5$ a_7	$-a_6$ $-a_4$	a_6 a_4	$-$ $-a_3a_4$
$-a_6$ $-a_4$	$-a_4$ a_5	$-a_7$ a_4	$-$ $-a_3a_5$
$-a_7$ a_4	$-$ $-a_3a_5$	$-a_3a_6$ $-$	$-a_3a_7$ $-$
a_6 a_4	$-$ $-a_3a_7$	$-a_3a_7$ $-$	$-a_3a_6$ $-$

and we hence see at once that the pairs of signs in the two columns respectively cannot be made identical to make them all $+$ we should have $a_4 = a_5$, $a_6 = -a_7$, $a_4 = a_7$, that is $a_4 = a_5 = a_6 = -a_7$ which is inconsistent with the last equation of the system $-a_3a_6 = -$. Hence the imaginaries 1, 2, 3, 4, 5, 6, 7, as defined by the original multiplication are not in any case associative.

If we have $a_1 = a_2 = a_3 = -$ and also $-a_1 = a_4 = a_5 = a_6 = +$ that is, if the imaginaries belong to the simplest form, then it is at once seen that each pair consists of two opposite signs: that is, for the several triads 123, 145, 167, 246, 257, 347, 356 used for the definition of the imaginaries the associative property holds good, $12.3 = 1.23$, etc., but for each of the remaining twenty-eight triads, the two terms are equal but of opposite signs, viz. $12.4 = -1.24$, etc., so that the product 124 of any such three symbols has no determinate meaning.

Baltimore, March 9th, 1882

On Certain Metrical Properties of Surfaces.

By Thomas Craig, *Johns Hopkins University.*

First consider a surface in a space of $n+1$ dimensions. For brevity in speaking of spaces of any number of dimensions I shall use the symbol (commonly employed) M_{n+1}; this is taken to denote a space of $n+1$ dimensions. A surface in M_{n+1} is understood to be expressed by a single relation between the $n+1$ coördinates which determine the position of a point in M_{n+1}. Denoting these coördinates by x_i where $i = 1, 2, 3 \ldots n+1$, the equation

$$\Phi(x_1\, x_2 \ldots x_{n+1}) = 0$$

is the equation of an n-dimensional surface in M_{n+1}. Since we have one relation connecting the $n+1$ quantities x_i, each of these may be given as a function of n independent variables $u_1\, u_2 \ldots u_n$.

Denote by $a_k^{(i)}$ the differential coefficient of x_i with respect to u_k, then

$$dx_i = a_1^{(i)}du_1 + a_2^{(i)}du_2 + \ldots + a_n^{(i)}du_n;$$

also denote by $a_{jk}^{(i)}$ the second differential coefficient of x_i with respect to u_j and u_k, then

$$d^2x_i = a_{11}^{(i)}du_1^2 + 2a_{12}^{(i)}du_1du_2 + 2a_{12}^{(i)}du_1du_2 + \ldots + a_{nn}^{(i)}du_n^2.$$

For the element of length ds of a curve traced on $\Phi = 0$, we have then

$$ds^2 = \sum_{i=1}^{i=n+1} a_1^{(i)2}du_1^2 + \Sigma a_2^{(i)2}du_2^2 + \ldots + \Sigma a_n^{(i)2}du_n^2 + 2\Sigma a_1^{(i)}a_2^{(i)}du_1du_2 + \ldots + 2\Sigma a_{n-1}^{(i)}a_n^{(i)}du_{n-1}\,du_n.$$

The limits of the summation have only been written once, as they are of course the same for every term. For brevity, write

$$E_{ii} = a_i^{(1)2} + a_i^{(2)2} + \ldots + a_i^{(n+1)2}$$
$$E_{jk} = a_j^{(1)}a_k^{(1)} + a_j^{(2)}a_k^{(2)} + \ldots + a_j^{(n)}a_k^{(n)};$$

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then for ds we have

$$ds^2 = E_{11}du_1^2 + E_{12}du_1du_2 + \ldots + E_{1n}du_1du_n + \ldots + E_{nn}du_n^2.$$

From the n quantities α_i form the determinants of $n-1$

$$\begin{matrix} \alpha_1^2 & \alpha_1^3 & \ldots & \alpha_1^{n-1} \\ \alpha_2^2 & \alpha_2^3 & \ldots & \alpha_2^{n-1} \\ \ldots & \ldots & \ldots & \ldots \\ \alpha_n^2 & \alpha_n^3 & \ldots & \alpha_n^{n-1} \end{matrix} = A_1$$

is the first. There will be $n-1$ of these determinants each of the degree n: squaring these and adding, we obtain, as is well known, a symmetrical determinant of the degree n, viz.

$$V^2 = \sum_1^n A_i^2 = \begin{matrix} E_{11} & E_{12} & E_{13} & \ldots & E_{1n} \\ E_{21} & E_{22} & E_{23} & \ldots & E_{2n} \\ E_{31} & E_{32} & E_{33} & \ldots & E_{3n} \\ \ldots & \ldots & \ldots & \ldots & \ldots \\ \ldots & \ldots & \ldots & \ldots & \ldots \\ E_{n1} & E_{n2} & E_{n3} & \ldots & E_{nn} \end{matrix} ;$$

of course $E_{ij} = E_{ji}$.

The differential equation of the surface $\Phi = 0$ can now be written as

$$A_1dx_1 + A_2dx_2 + \ldots + A_{n+1}dx_{n+1} = 0.$$

The direction-cosines of the normal to this surface at any point are

$$\alpha_1, \alpha_2, \ldots \alpha_{n+1} = \frac{A_1}{V}, \frac{A_2}{V}, \ldots \frac{A_{n+1}}{V}.$$

The element of area of the surface (as will be shown hereafter) is

$$dS = Vdu_1du_2 \ldots du_n,$$

or by virtue of the above relations,

$$dS = (\alpha_1A_1 + \alpha_2A_2 + \ldots + \alpha_{n+1}A_{n+1}) \prod_1^n du_i.$$

Suppose we have now a second surface

$$\Psi(y_1y_2 \ldots y_{n+1}) = 0$$

connected with the first by the relations

$$y_i = f_i(x_1x_2 \ldots x_{n+1}) \qquad i = 1, 2 \ldots n+1.$$

Denote by $\beta_1, \beta_2, \ldots \beta_{n+1}$ the direction-cosines of the normal to this second surface, and by $B_1, B_2 \ldots B_{n+1}$ what the determinants A_i of the first surface become for the second surface; then writing

$$U^2 = B_1^2 + B_2^2 + \ldots + B_{n+1}^2$$

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we have $$\beta_i = \frac{B_i}{U}$$

and for the element of area

$$d\Sigma = (\beta_1 B_1 + \beta_2 B_2 + \ldots + \beta_{n+1} B_{n+1}) \prod_1^n du_i .$$

The ratio between the elements of area dS and $d\Sigma$ is

$$\frac{d\Sigma}{dS} = \frac{U}{V}.$$

Now V may obviously be written in the form

$$V = \begin{vmatrix} a_1 & a_2 & a_3 & \ldots & a_{n+1} \\ \frac{dx_1}{du_1} & \frac{dx_2}{du_1} & \frac{dx_3}{du_1} & \ldots & \frac{dx_{n+1}}{du_1} \\ \frac{dx_1}{du_2} & \frac{dx_2}{du_2} & \frac{dx_3}{du_2} & \ldots & \frac{dx_{n+1}}{du_2} \\ \ldots & \ldots & \ldots & \ldots & \ldots \\ \frac{dx_1}{du_n} & \frac{dx_2}{du_n} & \frac{dx_3}{du_n} & \ldots & \frac{dx_{n+1}}{du_n} \end{vmatrix},$$

and similarly, denoting by $\left(\frac{dy_i}{du_k}\right)$ the quantity

$$\frac{dy_i}{dx_1}\frac{dx_1}{du_k} + \frac{dy_i}{dx_2}\frac{dx_2}{du_k} + \ldots + \frac{dy_i}{dx_{n+1}}\frac{dx_{n+1}}{du_k},$$

we may write

$$U = \begin{vmatrix} \beta_1 & \beta_2 & \beta_3 & \ldots & \beta_{n+1} \\ \left(\frac{dy_1}{du_1}\right) & \left(\frac{dy_2}{du_1}\right) & \left(\frac{dy_3}{du_1}\right) & \ldots & \left(\frac{dy_{n+1}}{du_1}\right) \\ \left(\frac{dy_1}{du_2}\right) & \left(\frac{dy_2}{du_2}\right) & \left(\frac{dy_3}{du_2}\right) & \ldots & \left(\frac{dy_{n+1}}{du_2}\right) \\ \ldots & \ldots & \ldots & \ldots & \ldots \\ \left(\frac{dy_1}{du_n}\right) & \left(\frac{dy_2}{du_n}\right) & \left(\frac{dy_3}{du_n}\right) & \ldots & \left(\frac{dy_{n+1}}{du_n}\right) \end{vmatrix}$$

The direction-cosines of the lines of intersection of the surfaces u taken $n-1$ at a time with the surface Φ are

$$\frac{1}{\sqrt{E_{11}}}\frac{dx_1}{du_1}, \quad \frac{1}{\sqrt{E_{11}}}\frac{dx_2}{du_1}, \quad \ldots \quad \frac{1}{\sqrt{E_{11}}}\frac{dx_{n+1}}{du_1},$$

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This is rather an interesting formula, and one which I have not been able to find given anywhere else; I actually obtained it first for three dimensions, but the generalization was obvious and attended with no difficulty, so for the purposes of another part of the paper I prefer to give it in this form at once. If we denote by x_1, x_2, x_3 the coördinates of a point on an ordinary surface, and by y_1, y_2, y_3 the coördinates of the corresponding point on a second surface, we have*

$$\frac{d\Sigma}{dS} = \frac{U}{V} = \begin{vmatrix} \beta_1 & \frac{dy_1}{dx_1} & \frac{dy_1}{dx_2} & \frac{dy_1}{dx_3} \\ \beta_2 & \frac{dy_2}{dx_1} & \frac{dy_2}{dx_2} & \frac{dy_2}{dx_3} \\ \beta_3 & \frac{dy_3}{dx_1} & \frac{dy_3}{dx_2} & \frac{dy_3}{dx_3} \\ 0 & \alpha_1 & \alpha_2 & \alpha_3 \end{vmatrix}, \text{ say } k.$$

Suppose the second surface to be a sphere of radius unity, whose radii are parallel to the normals at the corresponding point of the first surface. Let the first surface be given in the form

$$x_3 = \phi(x_1 x_2)$$

and denote by p and q the first differential coefficients of x_3 with respect to x_1 and x_2; also as usual write r, s, t for the second differential coefficients of x_3 with respect to x_1 and x_2.

The second surface is

$$y_1^2 + y_2^2 + y_3^2 = 1;$$

this is satisfied by writing

$$Y_1 = \frac{p}{Q}, \quad Y_2 = \frac{q}{Q}, \quad Y_3 = \frac{-1}{Q}$$

where $Q = \sqrt{1+p^2+q^2}$. The ratio between the corresponding elements of area on the two surfaces is now

$$\begin{vmatrix} \frac{p}{Q}, & \frac{(1+q^2)r - pqs}{Q^3}, & \frac{(1+q^2)s - pqt}{Q^3}, & 0 \\ \frac{q}{Q}, & \frac{(1+p^2)s - pqr}{Q^3}, & \frac{(1+p^2)t - pqs}{Q^3}, & 0 \\ \frac{-1}{Q}, & \frac{pr+qs}{Q^3}, & \frac{ps+qt}{Q^3}, & 0 \\ 0, & \frac{p}{Q}, & \frac{q}{Q}, & \frac{-1}{Q} \end{vmatrix}.$$

* Some time after the above had gone to press I was informed that Neumann had stated this theorem, without proof, for space of three dimensions, in Volume IX of the *Mathematische Annalen*.—T. C.

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The reduction of this to the ordinary form is quite easy. Write

$$\frac{A_1}{V},\ \frac{A_2}{V},\ \frac{A_3}{V} = \cos\theta_1,\ \cos\theta_2,\ \cos\theta_3,$$

and we have

$$k = \begin{vmatrix} \cos\theta_1, & -\sin\theta_1 \frac{d\theta_1}{dx_1}, & -\sin\theta_1 \frac{d\theta_1}{dx_2}, & -\sin\theta_1 \frac{d\theta_1}{dx_3} \\ \cos\theta_2, & -\sin\theta_2 \frac{d\theta_2}{dx_1}, & -\sin\theta_2 \frac{d\theta_2}{dx_2}, & -\sin\theta_2 \frac{d\theta_2}{dx_3} \\ \cos\theta_3, & -\sin\theta_3 \frac{d\theta_3}{dx_1}, & -\sin\theta_3 \frac{d\theta_3}{dx_2}, & -\sin\theta_3 \frac{d\theta_3}{dx_3} \\ 0, & \cos\theta_1, & \cos\theta_2, & \cos\theta_3, \end{vmatrix}.$$

Multiply the first row by $\cos\theta_1$, the second by $\cos\theta_2$, and the third by $\cos\theta_3$, and add the first and second rows to the third. The third row becomes now $1, 0, 0, 0$; interchanging the third and fourth rows, paying attention to all the signs, we have

$$k = \frac{\sin\theta_1 \sin\theta_2}{\cos\theta_3} \begin{vmatrix} \frac{d\theta_3}{dx_1} & \frac{d\theta_1}{dx_2} & \frac{d\theta_1}{dx_3} \\ \frac{d\theta_2}{dx_1} & \frac{d\theta_2}{dx_2} & \frac{d\theta_2}{dx_3} \\ \cos\theta_1 & \cos\theta_2 & \cos\theta_3 \end{vmatrix}$$

Now

$$\frac{d}{dx} = \frac{du_1}{dx}\frac{d}{du_1} + \frac{du_2}{dx}\frac{d}{du_2};$$

changing in the determinant differential coefficients with respect to x into differential coefficients with respect to u_1 and u_2, we have after some easy reductions,

$$k = \frac{1}{\cos\theta_3}\left\{\frac{d\cos\theta_1}{du_1}\frac{d\cos\theta_2}{du_2} - \frac{d\cos\theta_1}{du_2}\frac{d\cos\theta_2}{du_1}\right\}\left\{\cos\theta_1\left(\frac{du_1}{dx_2}\frac{du_2}{dx_3} - \frac{du_1}{dx_3}\frac{du_2}{dx_2}\right)\right.$$
$$\left. + \cos\theta_2\left(\frac{du_1}{dx_3}\frac{du_2}{dx_1} - \frac{du_1}{dx_1}\frac{du_2}{dx_3}\right) + \cos\theta_3\left(\frac{du_1}{dx_1}\frac{du_2}{dx_2} - \frac{du_1}{dx_2}\frac{du_2}{dx_1}\right)\right\}.$$

Denote by E'_{11}, E'_{12}, E'_{22} the determinants

$$\begin{vmatrix} \frac{d^2x_1}{du_1^2} & \frac{d^2x_2}{du_1^2} & \frac{d^2x_3}{du_1^2} \\ \frac{dx_1}{du_1} & \frac{dx_2}{du_1} & \frac{dx_3}{du_1} \\ \frac{dx_1}{du_2} & \frac{dx_2}{du_2} & \frac{dx_3}{du_2} \end{vmatrix}, \quad \begin{vmatrix} \frac{d^2x_1}{du_1 du_2} & \frac{d^2x_2}{du_1 du_2} & \frac{d^2x_3}{du_1 du_2} \\ \frac{dx_1}{du_1} & \frac{dx_2}{du_1} & \frac{dx_3}{du_1} \\ \frac{dx_1}{du_2} & \frac{dx_2}{du_2} & \frac{dx_3}{du_2} \end{vmatrix}, \quad \begin{vmatrix} \frac{d^2x_1}{du_2^2} & \frac{d^2x_2}{du_2^2} & \frac{d^2x_3}{du_2^2} \\ \frac{dx_1}{du_1} & \frac{dx_2}{du_1} & \frac{dx_3}{du_1} \\ \frac{dx_1}{du_2} & \frac{dx_2}{du_2} & \frac{dx_3}{du_2} \end{vmatrix}.$$

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The quantities A_1, A_2, A_3 are the minors of these corresponding to the constituents of the first row in each. We find now readily

$$\frac{d\cos\theta_1}{du_1} = \frac{d}{du_1}\cdot\frac{A_1}{V} = -\frac{1}{V^3}\left[\left(E_{11}F_{12}-E_{12}E_{11}\right)\frac{dx_1}{du_1}+\left(E_{12}E_{11}-E_{11}E_{12}\right)\frac{dx_2}{du_1}\right]$$

$$\frac{d\cos\theta_1}{du_2} = \frac{d}{du_2}\cdot\frac{A_1}{V} = -\frac{1}{V^3}\left[\left(E_{12}F_{12}-E_{12}E_{12}\right)\frac{dx_1}{du_2}+\left(E_{12}E_{11}-E_{11}E_{12}\right)\frac{dx_2}{du_2}\right]$$

$$\frac{d\cos\theta_2}{du_1} = \frac{d}{du_1}\cdot\frac{A_2}{V} = -\frac{1}{V^3}\left[\left(E_{11}F_{22}-E_{12}E_{21}\right)\frac{dx_1}{du_1}+\left(E_{12}E_{21}-E_{11}E_{22}\right)\frac{dx_2}{du_1}\right]$$

$$\frac{d\cos\theta_2}{du_2} = \frac{d}{du_2}\cdot\frac{A_2}{V} = -\frac{1}{V^3}\left[\left(E_{12}F_{22}-E_{22}E_{21}\right)\frac{dx_1}{du_2}+\left(E_{22}E_{21}-E_{21}E_{22}\right)\frac{dx_2}{du_2}\right]$$

$$\frac{d\cos\theta_3}{du_1} = \frac{d}{du_1}\cdot\frac{A_3}{V} = -\frac{1}{V^3}\left[\left(E_{11}F_{12}-E_{12}E_{11}\right)\frac{dx_1}{du_1}+\left(E_{12}E_{11}-E_{11}E_{12}\right)\frac{dx_2}{du_1}\right]$$

$$\frac{d\cos\theta_3}{du_2} = \frac{d}{du_2}\cdot\frac{A_3}{V} = -\frac{1}{V^3}\left[\left(E_{12}F_{12}-E_{12}E_{12}\right)\frac{dx_1}{du_2}+\left(E_{12}E_{11}-E_{11}E_{12}\right)\frac{dx_2}{du_2}\right]$$

Substituting these values in the first factor in brackets in the expression for k, we have, after easy reductions, for this factor the value

$$\frac{E_{11}E_{22}F_{12}^2}{V^4}\left(\frac{dx_1}{du_1}\frac{dx_2}{du_2}-\frac{dx_1}{du_2}\frac{dx_2}{du_1}\right) = A_1\frac{E_{11}E_{22}-E_{12}^2}{V^4} = \cos\theta_1\frac{E_{11}E_{22}-E_{12}^2}{V^2}.$$

The remaining factor in brackets becomes obviously

$$\frac{A_1^2+A_2^2+A_3^2}{V^2} = \frac{1}{V}.$$

So finally collecting all the terms we have

$$k = \frac{E_{11}E_{22}-E_{12}^2}{V^4},$$

or in the ordinary notation,

$$k = \frac{E'G-F'^2}{(EG-F^2)^2}$$

the well-known form for the measure of curvature. We have, then, the theorem that if $\cos\theta_1$, $\cos\theta_2$, $\cos\theta_3$ are the direction-cosines of the normal at any point x, y, z of a surface, the measure of curvature of the surface at this point is given by

$$k = \begin{vmatrix} \cos\theta_1, & \frac{d\cos\theta_1}{dx} & \frac{d\cos\theta_1}{dy} & \frac{d\cos\theta_1}{dz} \\ \cos\theta_2, & \frac{d\cos\theta_2}{dx} & \frac{d\cos\theta_2}{dy} & \frac{d\cos\theta_2}{dz} \\ \cos\theta_3, & \frac{d\cos\theta_3}{dx} & \frac{d\cos\theta_3}{dy} & \frac{d\cos\theta_3}{dz} \\ 0 & \cos\theta_1 & \cos\theta_2 & \cos\theta_3 \end{vmatrix}$$

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or again by

$$k = \frac{\sin\theta_1 \sin\theta_2}{\cos\theta_3} \begin{vmatrix} \frac{d\theta_1}{dx} & \frac{d\theta_1}{dy} & \frac{d\theta_1}{dz} \\ \frac{d\theta_2}{dx} & \frac{d\theta_2}{dy} & \frac{d\theta_2}{dz} \\ \cos\theta_1 & \cos\theta_2 & \cos\theta_3 \end{vmatrix}.$$

There are of course two other forms similar to this got by advancing the suffixes of θ. The bordered determinant whose value in the general case is K may in like manner be shown to be equal to

$$\frac{V'}{V^{n+1}},$$

where V' is the result of accenting all the letters in V just as has been done in the case of an ordinary surface and a unit sphere, so that $\frac{V'}{V^{n+2}}$ is the measure of curvature of a surface

$$\Phi(x_1 x_2 \ldots x_{n+1}) = 0$$

in M_{n+1}, the unit sphere being

$$Y_1^2 + Y_2^2 + \ldots + Y_{n+1}^2 = 1.$$

The correspondence between the surface $\Phi = 0$ and the n-dimensional unit sphere is of course just the same as in the ordinary case. The direction-cosines of the normal to Φ are

$$\frac{\Phi_1}{Q}, \quad \frac{\Phi_2}{Q}, \quad \ldots \quad \frac{\Phi_{n+1}}{Q}$$

the subscripts indicating differential coefficients and

$$Q = \sqrt{\sum_1^{n+1} \Phi_i^2}.$$

The required correspondence between the surface Φ and the sphere is produced by writing

$$Y_i = \frac{\Phi_i}{Q}.$$

Consider consecutive points on both surfaces: on the surface Φ these are given by

$$(x_1, x_2 \ldots x_{n+1}), \left(x_1 + \frac{dx_1}{du_i} du_i, x_2 + \frac{dx_2}{du_i} du_i \ldots\right)$$

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G is the volume of the parallelopipedon, δ its slant height, and obviously $\delta \cos\theta$ its altitude; consequently $\frac{G}{\delta \cos\theta}$ is the base, or the element of the surface Φ is given by the quantity $V \cdot \prod_1^n du_i$.

This is the value of dS that has been employed. The proof that I have given is similar to one given by Beez in the *Math. Ann.;* but as I obtained my proof before reading Beez's article, and as the two proofs differ considerably in the methods of working them out, I let mine stand just as I obtained it. It is obvious that for the correspondence between the sphere and the surface Φ required in order to find the value of the measure of curvature, it is only necessary to write

$$Y_i = \frac{A}{V}$$

and so

$$\frac{dy_i}{du_k} = \frac{1}{V^2}\left\{ V\frac{dA_i}{du_k} - A_i\frac{dV}{du_k}\right\}.$$

Consider the determinant B_1, *i. e.*

$$B_1 = \begin{vmatrix} \frac{dy_2}{du_1} & \frac{dy_2}{du_2} & \cdots & \frac{dy_2}{du_n} \\ \frac{dy_3}{du_1} & \frac{dy_3}{du_2} & \cdots & \frac{dy_3}{du_n} \\ \cdots & \cdots & \cdots & \cdots \\ \frac{dy_{n+1}}{du_1} & \frac{dy_{n+1}}{du_2} & \cdots & \frac{dy_{n+1}}{du_n} \end{vmatrix}.$$

Substituting in this the value of each constituent as given by the above formula, we find after simple reductions,

$$B_1 = \frac{1}{V^{n+2}} \begin{vmatrix} V^2 & A_2 & A_3 & \cdots & A_{n+1} \\ \frac{1}{2}\frac{dV^2}{du_1} & \frac{dA_2}{du_1} & \frac{dA_3}{du_1} & \cdots & \frac{dA_{n+1}}{du_1} \\ \frac{1}{2}\frac{dV^2}{du_2} & \frac{dA_2}{du_2} & \frac{dA_3}{du_2} & \cdots & \frac{dA_{n+1}}{du_2} \\ \cdots & \cdots & \cdots & \cdots & \cdots \\ \frac{1}{2}\frac{dV^2}{du_n} & \frac{dA_2}{du_n} & \frac{dA_3}{du_n} & \cdots & \frac{dA_{n+1}}{du_n} \end{vmatrix}.$$

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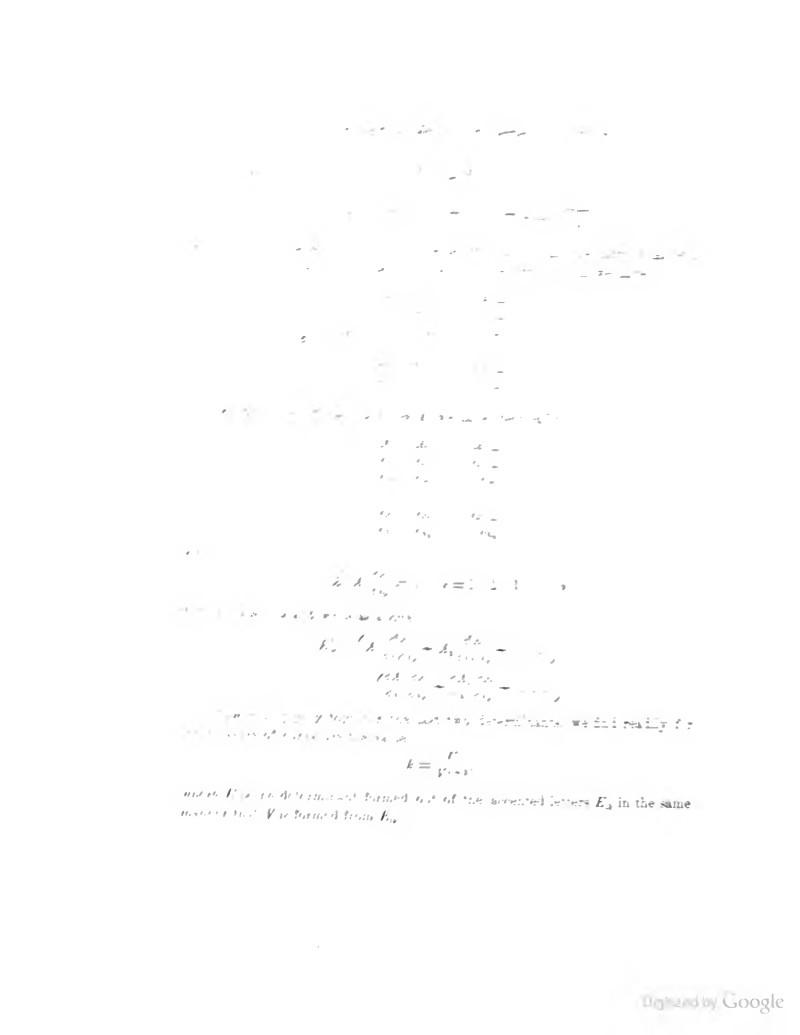

$$k = \frac{V}{V_{\text{circ.}}}$$

where V is the determinant formed out of the accented letters E_a in the same manner that V is formed from E_a.

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It is not necessary to go into the proof that the determinant

$$\begin{vmatrix} \frac{A_1}{V} & \frac{d}{du_1}\frac{A_1}{V} & \cdots & \frac{d}{du_n}\frac{A_1}{V} \\ \frac{A_2}{V} & \frac{d}{du_1}\frac{A_2}{V} & \cdots & \frac{d}{du_n}\frac{A_2}{V} \\ \cdots & \cdots & \cdots & \cdots \\ \cdots & \cdots & \cdots & \cdots \\ \frac{A_{n+1}}{V} & \frac{d}{du_1}\frac{A_{n+1}}{V} & \cdots & \frac{d}{du_n}\frac{A_{n+1}}{V} \\ 0 & \frac{A_1}{V} & \cdots & \frac{A_{n+1}}{V} \end{vmatrix}$$

reduces in this case, as in the simple one of $n = 2$, to the ratio

$$\frac{U}{V^{n+2}}$$

and consequently that this bordered determinant gives the measure of curvature for the n-dimensional surface $\Phi = 0$ in M_{n+1}.

In seeking the expression for the radii of curvature of the surface $\Phi = 0$ at any point, it will be sufficient to consider the case of $n + 1 = 4$.

Denote by ξ_1, ξ_2, ξ_3, ξ_4 the coördinates of any point on the normal to $\Phi = 0$ at the point x_1, x_2, x_3, x_4; then

$$\xi_i = x_i + A_i\lambda, \qquad i = 1, 2, 3, 4.$$

Suppose (ξ) to be the point where this normal meets the consecutive normal, then

$$dx_i + A_i d\lambda + \lambda dA_i = 0;$$

but

$$dx_i = a_1^{(i)}du_1 + a_2^{(i)}du_2 + a_3^{(i)}du_3,$$

and similarly we may write

$$dA_i = A_1^{(i)}du_1 + A_2^{(i)}du_2 + A_3^{(i)}du_3;$$

consequently

$$(a_1^{(i)} + \lambda A_1^{(i)})\,du_1 + \ldots + A_i d\lambda = 0, \qquad i = 1, 2, 3, 4.$$

Eliminating du_1, du_2, du_3 and $d\lambda$ from these we obtain

$$\begin{vmatrix} a_1^{(1)} + \lambda A_1^{(1)}, & a_2^{(1)} + \lambda A_2^{(1)}, & a_3^{(1)} + \lambda A_3^{(1)}, & A_1 \\ a_1^{(2)} + \lambda A_1^{(2)}, & a_2^{(2)} + \lambda A_2^{(2)}, & a_3^{(2)} + \lambda A_3^{(2)}, & A_2 \\ a_1^{(3)} + \lambda A_1^{(3)}, & a_2^{(3)} + \lambda A_2^{(3)}, & a_3^{(3)} + \lambda A_3^{(3)}, & A_3 \\ a_1^{(4)} + \lambda A_1^{(4)}, & a_2^{(4)} + \lambda A_2^{(4)}, & a_3^{(4)} + \lambda A_3^{(4)}, & A_4 \end{vmatrix} = 0.$$

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Calling ρ the radius of curvature, we have $\rho^2 = \Sigma\ \xi_i - x_i^{\ 0} = \lambda^2 V^2$, and consequently

$$\lambda = \frac{\circ}{V}.$$

Substituting this in the previous equations and making the simple reduction, the equation becomes

$$\begin{vmatrix} E_{11}V + \rho\Sigma A_1^{\ 1}\alpha_1^{\ 1}, & E_{12}V + \rho\Sigma A_1^{\ 1}\alpha_2^{\ 1}, & E_{13}V + \rho\Sigma A_1^{\ 1}\alpha_3^{\ 1}, \\ E_{21}V + \rho\Sigma A_1^{\ 2}\alpha_1^{\ 2}, & E_{22}V + \rho\Sigma A_2^{\ 2}\alpha_2^{\ 2}, & E_{23}V + \rho\Sigma A_2^{\ 2}\alpha_3^{\ 2}, \\ E_{31}V + \rho\Sigma A_1^{\ 3}\alpha_1^{\ 3}, & E_{32}V + \rho\Sigma A_2^{\ 3}\alpha_2^{\ 3}, & E_{33}V + \rho\Sigma A_3^{\ 3}\alpha_3^{\ 3} \end{vmatrix} = 0.$$

Introduce here the accented letters E'_{ik}, viz.

$$E'_{ik} = A_i b_{1k}^{\ 1} + A_j b_{2k}^{\ 2} + A_l b_{3k}^{\ 3}$$

in which

$$b_{ik} = \frac{d^2 x_i}{da_i^2} = \frac{d\alpha_i^0}{da_k},$$

$$b_{jk}^{\ i} = \frac{d^2 x_i}{da_j da_k} = \frac{d\alpha_j^{\ i}}{da_k} = \frac{d\alpha_k^{\ i}}{da_j}.$$

Differentiate the identity

$$\sum_{j=1}^{j=4} A_j \alpha_i^{\ j} = 0$$

and we obtain

$$\sum_{j=1}^{j=4} \alpha_i^{\ j} A_i^{\ j} = -\sum_{j=1}^{j=4} A_j b_{ii}^{\ j}$$

There are in all six equations of this kind; the quantities on the left hand side of each of these equations are the coefficients of ρ in the above cubic equation, while the quantities on the right are equal to

$$-E_{11},\ -E_{22},\ -E_{33},\ -E_{12},\ -E_{31},\ -E_{23}.$$

The cubic equation for the determination of ρ becomes now

$$\begin{vmatrix} E'_{11}\rho - E_{11}V, & E'_{12}\rho - E_{12}V, & E'_{13}\rho - E_{13}V \\ E'_{21}\rho - E_{21}V, & E'_{22}\rho - E_{22}V, & E'_{23}\rho - E_{23}V \\ E'_{31}\rho - E_{31}V, & E'_{32}\rho - E_{32}V, & E'_{33}\rho - E_{33}V \end{vmatrix} = 0.$$

The equation for the determination of the radii of curvature of $\Phi = 0$ in M_{n+1} is obviously

$$\begin{vmatrix} E'_{11}\rho - E_{11}V, & E'_{12}\rho - E_{12}V \ldots & E'_{1n}\rho - E_{1n}V \\ E'_{21}\rho - E_{21}V, & E'_{22}\rho - E_{22}V \ldots & E'_{2n}\rho - E_{2n}V \\ \ldots\ldots\ldots\ldots\ldots\ldots\ldots & & \\ E'_{n1}\rho - E_{n1}V, & E'_{n2}\rho - E_{n2}V \ldots & E'_{nn}\rho - E_{nn}V \end{vmatrix} = 0.$$

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The coefficient of ρ^n in this is U, where as before

$$U^2 = |E'_{jk}|, \qquad V^2 = |E_{jk}|,$$

and the constant term is V^{n+2}. Consequently denoting by $\rho_1, \rho_2 \ldots \rho_n$ the roots of this equation, we have

$$\frac{1}{\rho_1 \rho_2 \cdots \rho_n} = \frac{U}{V^{n+2}},$$

the value of the measure of curvature.

The equation

$$U = V^{n+2}$$

is the differential equation of all surfaces developable upon the n-dimensional sphere. The result of equating the coefficient of ρ to zero, *i. e.*

$$\rho_1 + \rho_2 + \ldots + \rho_n = 0$$

corresponds to a class of surfaces similar to surfaces of minimum area.

Denoting by $\alpha_1, \alpha_2, \alpha_3$ the direction-cosines of a normal to the surface $\Phi(x_1 x_2 x_3) = 0$ and by $\beta_1, \beta_2, \beta_3$ the direction-cosines to the second surface at the corresponding point, write

$$\begin{aligned}
l_1, \quad l_2, \quad l_3 &= \frac{d\alpha_1}{du_1}, \quad \frac{d\alpha_2}{du_1}, \quad \frac{d\alpha_3}{du_1} \\
m_1, \quad m_2, \quad m_3 &= \frac{d\alpha_1}{du_2}, \quad \frac{d\alpha_2}{du_2}, \quad \frac{d\alpha_3}{du_2} \\
\lambda_1, \quad \lambda_2, \quad \lambda_3 &= \frac{d\beta_1}{du_1}, \quad \frac{d\beta_2}{du_1}, \quad \frac{d\beta_3}{du_1} \\
\mu_1, \quad \mu_2, \quad \mu_3 &= \frac{d\beta_1}{du_2}, \quad \frac{d\beta_2}{du_2}, \quad \frac{d\beta_3}{du_2}.
\end{aligned}$$

Then obviously

$$\begin{vmatrix} \alpha_1 & \alpha_2 & \alpha_3 \\ l_1 & l_2 & l_3 \\ m_1 & m_2 & m_3 \end{vmatrix} = Vk,$$

and, calling K the measure of curvature of the second surface,

$$\begin{vmatrix} \beta_1 & \beta_2 & \beta_3 \\ \lambda_1 & \lambda_2 & \lambda_3 \\ \mu_1 & \mu_2 & \mu_3 \end{vmatrix} = UK.$$

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[illegal]

$$\begin{matrix} z_1 & z_2 & z_3 & 1 & 1 \\ x_1 & x_2 & x_3 & 1 & 1 \\ u_1 & u_2 & u_3 & 1 & 1 \\ A_1 & A_2 & A_3 & E & F \\ A_1 & A_2 & A_3 & G & H \\ B_1 & B_2 & B_3 & F & G \\ B_1 & B_2 & B_3 & H & K \end{matrix}$$

$$= V^2 L^2 K$$

$$\frac{A_1}{A_2} - \frac{A_1}{A_3} = \frac{A_1}{A_2} - \frac{A_2}{A_3} = \frac{A_2}{A_3} - \frac{A_3}{A_1}$$

$$V \begin{vmatrix} z_1 & y_1 & z_1 & dx_1 & dy_1 & dz_1 \\ z_2 & y_2 & z_2 & dx_2 & dy_2 & dz_2 \\ z_3 & y_3 & z_3 & dx_3 & dy_3 & dz_3 \\ 0 & 0 & 0 & x_1 & x_2 & x_3 \\ 0 & 0 & 0 & l_1 & l_2 & l_3 \\ 0 & 0 & 0 & m_1 & m_2 & m_3 \end{vmatrix}$$

This is obviously $= V^2 L^2 K$, so that no results of any consequence can be obtained by bordering the functional determinant

$$d(y_1 y_2 y_3)$$
$$d(x_1 x_2 x_3)$$

in this manner. Take the determinant

$$\begin{vmatrix} dx_1 & dx_1 & dy_1 & dy_1 & dy_1 \\ du_2 & du_3 & dx_1 & dx_2 & dx_3 \\ dx_2 & dx_3 & dy_2 & dy_2 & dy_2 \\ du_3 & du_1 & dx_3 & dx_3 & dx_3 \\ dx_3 & dx_1 & dy_3 & dy_3 & dy_3 \\ du_1 & du_2 & dx_1 & dx_1 & dx_3 \\ 0 & 0 & dx_1 & dx_2 & dx_3 \\ & & du_2 & du_3 & du_1 \\ 0 & 0 & dx_1 & dx_2 & dx_3 \\ & & du_3 & du_1 & du_2 \end{vmatrix} = \Delta$$

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and multiply this by the determinant giving V^2, bordered in a suitable manner. The product is readily found to give

$$-V^2\begin{vmatrix} \frac{dx_1}{du_1} & \frac{dx_2}{du_1} & \frac{dx_3}{du_1} \\ \frac{dx_1}{du_2} & \frac{dx_2}{du_2} & \frac{dx_3}{du_2} \\ \Sigma A\frac{dy_1}{dx} & \Sigma A\frac{dy_2}{dx} & \Sigma A\frac{dy_3}{dx} \end{vmatrix}$$

$$= -V^2\left\{A_1\Sigma A_4\frac{dy_1}{dx_4} + A_2\Sigma A_4\frac{dy_2}{dx_4} + A_3\Sigma A_4\frac{dy_3}{dx_4}\right\}$$

$$= -V^2\Sigma A_4\Sigma A_4\frac{dy_3}{dx_4}.$$

Substituting for $\frac{dy}{dx}$ the value

$$\frac{dy}{du_1}\frac{du_1}{dx} + \frac{dy}{du_2}\frac{du_2}{dx},$$

and dropping the factor V^2, we have

$$-\Delta = \Sigma A_4\frac{du_1}{dx_4}\Sigma A_4\frac{dy_4}{du_1} + \Sigma A_4\frac{du_2}{dx_4}\Sigma A_4\frac{dy_4}{du_2}.$$

The first of the factors in this expression is proportional to the cosine of the angle between the normals to the surfaces $\Phi = 0$ and $u_1 = \text{const.}$ The second factor is proportional to the cosine of the angle between the normal to $\Phi = 0$ and the tangent to the curve $u_1 = \text{const.}$ traced on the second surface—say $\Psi = 0$. The first factor of the last term is proportional to the cosine of the angle between the normals to $\Phi = 0$ and $u_2 = \text{const.}$, and the last factor is proportional to the cosine of the angle between the normal to $\Phi = 0$ and the tangent to the curve $u_2 = \text{const.}$, $\Psi = 0$. Call these angles θ_1, ϕ_1, θ_2, ϕ_2, and write

$$\Sigma\left(\frac{dy_4}{du_1}\right)^2 = \mathcal{G}, \quad \Sigma\left(\frac{dy_4}{du_2}\right)^2 = \mathcal{D}, \quad \Sigma\frac{dy_4}{du_1}\frac{dy_4}{du_2} = \mathcal{M},$$

$$\Sigma\left(\frac{du_1}{dx_4}\right)^2 = L, \quad \Sigma\left(\frac{du_2}{dx_4}\right)^2 = M; \text{ we have then at once}$$

$$-\Delta = V^2\{\mathcal{G}L\cos\theta_1\cos\phi_1 + \mathcal{D}M\cos\theta_2\cos\phi_2\}.$$

If the surfaces $u = \text{const.}$ intersect $\Phi = 0$ orthogonally, we have $\cos\theta_1 = \cos\theta_2 = 0$ and so $\Delta = 0$. If $\cos\phi_1 = \cos\phi_2 = 0$, all the normals to the surface $\Phi = 0$ will be parallel to the normals at the corresponding points of $\Psi = 0$.

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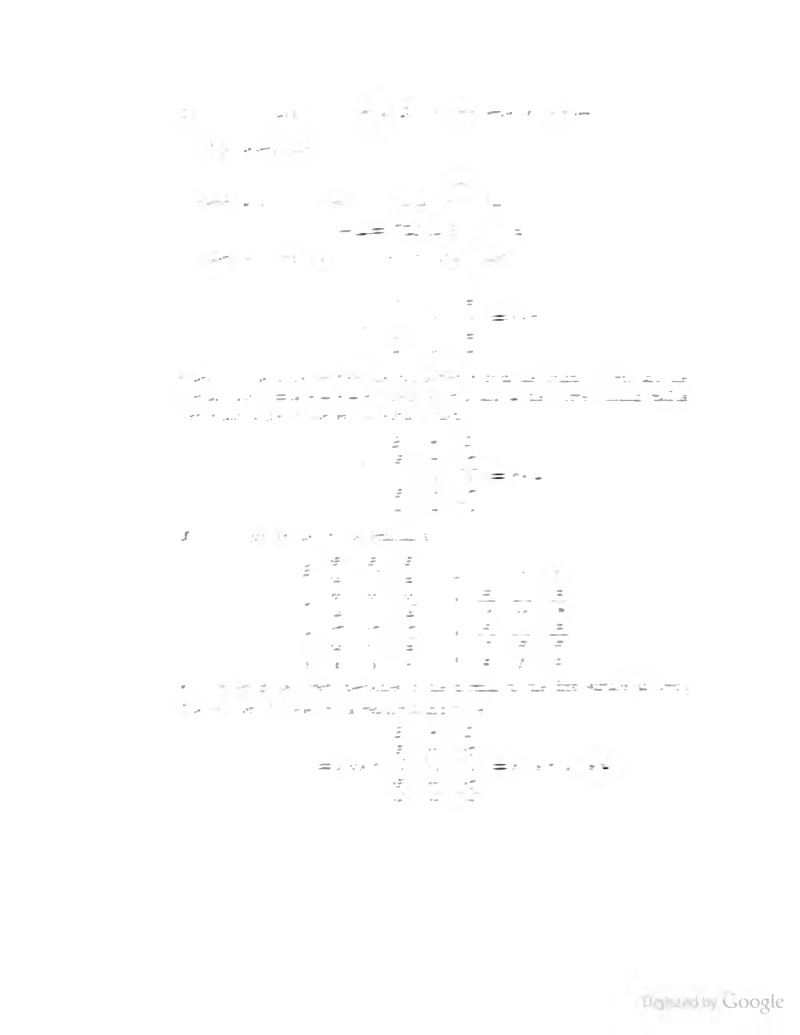

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therefore

$$\cos\psi = \frac{1}{\rho}\begin{vmatrix} \xi & \frac{d\xi}{dx} & \frac{d\xi}{dy} & \frac{d\xi}{dz} \\ \eta & \frac{d\eta}{dx} & \frac{d\eta}{dy} & \frac{d\eta}{dz} \\ \zeta & \frac{d\zeta}{dx} & \frac{d\zeta}{dy} & \frac{d\zeta}{dz} \\ 0 & a & b & c \end{vmatrix}.$$

The ratio between the corresponding elements of area on two corresponding surfaces (xyz), $(\xi\eta\zeta)$ has been shown to be $=$

$$\begin{vmatrix} \alpha & \frac{d\xi}{dx} & \frac{d\xi}{dy} & \frac{d\xi}{dz} \\ \beta & \frac{d\eta}{dx} & \frac{d\eta}{dy} & \frac{d\eta}{dz} \\ \gamma & \frac{d\zeta}{dx} & \frac{d\zeta}{dy} & \frac{d\zeta}{dz} \\ 0 & a & b & c \end{vmatrix} = -\frac{U}{V}.$$

This can be given in a different form in the case when the surfaces

$$\xi = F_1(xyz)$$
$$\eta = F_2(xyz)$$
$$\zeta = F_3(xyz)$$

are orthogonal. The coördinates of a point on the second surface may be considered as given by the intersection of the three surfaces

$$F_1 = \text{const.}, \quad F_2 = \text{const.}, \quad F_3 = \text{const.}$$

The conditions for orthogonality of these surfaces are, writing ξ, η, ζ instead of F_1, F_2, F_3,

$$\frac{d\xi}{dx}\frac{d\eta}{dx} + \frac{d\xi}{dy}\frac{d\eta}{dy} + \frac{d\xi}{dz}\frac{d\eta}{dz} = 0$$
$$\frac{d\eta}{dx}\frac{d\zeta}{dx} + \frac{d\eta}{dy}\frac{d\zeta}{dy} + \frac{d\eta}{dz}\frac{d\zeta}{dz} = 0$$
$$\frac{d\zeta}{dx}\frac{d\xi}{dx} + \frac{d\zeta}{dy}\frac{d\xi}{dy} + \frac{d\zeta}{dz}\frac{d\xi}{dz} = 0.$$

Find the product of the last given determinant and the functional determinant

$$\frac{d(\xi\eta\zeta)}{d(xyz)}$$

bordered by 1, 0, 0, 0 for its first row and by the same for its first column.

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Write

$$\left(\frac{d\xi}{dx}\right)^2 + \left(\frac{d\xi}{dy}\right)^2 + \left(\frac{d\xi}{dz}\right)^2 = \Xi^2$$
$$\left(\frac{d\eta}{dx}\right)^2 + \left(\frac{d\eta}{dy}\right)^2 + \left(\frac{d\eta}{dz}\right)^2 = H^2$$
$$\left(\frac{d\zeta}{dx}\right)^2 + \left(\frac{d\zeta}{dy}\right)^2 + \left(\frac{d\zeta}{dz}\right)^2 = Z^2.$$

We have, then, for the required product

$$\begin{matrix} \alpha & \beta & \gamma & 0 \\ \Xi^2 & 0 & 0 & \Xi\cos\theta_1 \\ 0 & H^2 & 0 & H\cos\theta_2 \\ 0 & 0 & Z^2 & Z\cos\theta_3 \end{matrix}$$

where θ_1, θ_2, θ_3 are the angles which the normal to the original surface makes with the normals to the surfaces ξ, η, ζ at their common point of intersection. Expanding this we have

$$\Xi HZ\{HZ\alpha\cos\theta_1 + Z\Xi\beta\cos\theta_2 + \Xi H\gamma\cos\theta_3\}$$

and consequently

$$\frac{U}{V} = \frac{-\Xi HZ}{\frac{d(\xi\eta\zeta)}{d(xyz)}}\left\{HZ\alpha\cos\theta_1 + Z\Xi\beta\cos\theta_2 + \Xi H\gamma\cos\theta_3\right\}$$

or

$$= \frac{-\Xi^2H^2Z^2}{\frac{d(\xi\eta\zeta)}{d(xyz)}}\left\{\frac{\alpha\cos\theta_1}{\Xi} + \frac{\beta\cos\theta_2}{H} + \frac{\gamma\cos\theta_3}{Z}\right\}$$

If we denote for the moment by

$$\begin{matrix} \alpha_1 & \beta_1 & \gamma_1 \\ \alpha_2 & \beta_2 & \gamma_2 \\ \alpha_3 & \beta_3 & \gamma_3 \end{matrix}$$

the direction-cosines of the normals to the surfaces ξ, η, ζ respectively, we have

$$\frac{d(\xi\eta\zeta)}{d(xyz)} = \Xi HZ\begin{vmatrix} \alpha_1 & \beta_1 & \gamma_1 \\ \alpha_2 & \beta_2 & \gamma_2 \\ \alpha_3 & \beta_3 & \gamma_3 \end{vmatrix} = \Xi HZ;$$

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and consequently

$$\frac{d\Sigma}{dS'} = \frac{U}{V'} = -\Xi HZ\left\{\frac{\alpha\cos\theta_1}{\Xi} + \frac{\beta\cos\theta_2}{H} + \frac{\gamma\cos\theta_3}{Z}\right\}.$$

Of course a similar formula applies for a surface of n dimensions in M_{n+1}.

I will now work out a few simple properties of curves in a space of more than three dimensions. The results obtained are (with one exception which is referred to below) I believe new. For simplicity, at first consider only a space of four dimensions—M_4. A curve in M_4 in the ordinary acceptation of that term will depend only on one parameter—it may either be given by the values of its coördinates expressed as functions of this parameter, or as the intersection of three 3-dimensional surfaces, say

$$\Phi_1 = 0, \quad \Phi_2 = 0, \quad \Phi_3 = 0.$$

Let u denote the parameter. First obtain the equation of the osculating flat space of three dimensions at any point of the curve. Four points on the curve will determine the osculating 3-flat. Take then four points on the curve, say A, B, C, D. The coördinates are

A	B	C	D
x_1	$x_1 + \Delta x_1$	$x_1 + 2\Delta x_1 + \Delta^2 x_1$	$x_1 + 3\Delta x_1 + 3\Delta^2 x_1 + \Delta^3 x_1$
x_2	$x_2 + \Delta x_2$	$x_2 + 2\Delta x_2 + \Delta^2 x_2$	$x_2 + 3\Delta x_2 + 3\Delta^2 x_2 + \Delta^3 x_2$
x_3	$x_3 + \Delta x_3$	$x_3 + 2\Delta x_3 + \Delta^2 x_3$	$x_3 + 3\Delta x_3 + 3\Delta^2 x_3 + \Delta^3 x_3$
x_4	$x_4 + \Delta x_4$	$x_4 + 2\Delta x_4 + \Delta^2 x_4$	$x_4 + 3\Delta x_4 + 3\Delta^2 x_4 + \Delta^3 x_4$

Now if $(\xi_1, \xi_2, \xi_3, \xi_4)$ is any point in the 3-flat passing through (x), its equation is

$$a_1(\xi_1 - x_1) + a_2(\xi_2 - x_2) + a_3(\xi_3 - x_3) + a_4(\xi_4 - x_4) = 0.$$

Substitute for (ξ) the coördinates of B and we have

$$a_1\Delta x_1 + a_2\Delta x_2 + a_3\Delta x_3 + a_4\Delta x_4 = 0.$$

In like manner substituting the coördinates of C and D in the place of (ξ), and using this last result to reduce the result of substituting the coördinates of C, and similarly reducing in the case of the point D, we have

$$\Sigma a\Delta^3 x = 0 \qquad \Sigma a\Delta^4 x = 0.$$

Eliminating (a) from the four equations,

$$\Sigma a(\xi - x) = 0 \qquad \Sigma a\Delta x = 0$$
$$\Sigma a\Delta^2 x = 0 \qquad \Sigma a\Delta^3 x = 0,$$

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The direction-cosines of the perpendicular to the osculating 3-flat are

$$\alpha_1,\ \beta_1,\ \gamma_1,\ \kappa_1 = \frac{1}{Q}\begin{vmatrix} \frac{dx_2}{du} & \frac{dx_3}{du} & \frac{dx_4}{du} \\ \frac{d^2x_2}{du^2} & \frac{d^2x_3}{du^2} & \frac{d^2x_4}{du^2} \\ \frac{d^3x_2}{du^3} & \frac{d^3x_3}{du^3} & \frac{d^3x_4}{du^3} \end{vmatrix}, \text{ \&c.}$$

where of course

$$Q = \begin{vmatrix} \Sigma\left(\frac{dx}{du}\right)^2, & \Sigma\frac{dx}{du}\frac{d^2x}{du^2}, & \Sigma\frac{dx}{du}\frac{d^3x}{du^3} \\ \Sigma\frac{dx}{du}\frac{d^2x}{du^2}, & \Sigma\left(\frac{d^2x}{du^2}\right)^2, & \Sigma\frac{d^2x}{du^2}\frac{d^3x}{du^3} \\ \Sigma\frac{dx}{du}\frac{d^3x}{du^3}, & \Sigma\frac{d^2x}{du^2}\frac{d^3x}{du^3}, & \Sigma\left(\frac{d^3x}{du^3}\right)^2 \end{vmatrix}$$

Suppose we make s the independent variable, then

$$\Sigma\left(\frac{dx}{ds}\right)^2 = 1$$

and

$$\Sigma\frac{dx}{ds}\frac{d^2x}{ds^2} = \frac{1}{2}\,d\Sigma\left(\frac{dx}{ds}\right)^2 = 0,$$

$$\Sigma\frac{dx}{ds}\frac{d^3x}{ds^3} = d\Sigma\frac{dx}{ds}\frac{d^2x}{ds^2} - d\Sigma\left(\frac{dx}{ds}\right)^2 = -\,d\Sigma\left(\frac{dx}{ds}\right)^2,$$

$$\Sigma\frac{d^2x}{ds^2}\frac{d^3x}{ds^3} = \frac{1}{2}\,d\Sigma\left(\frac{d^2x}{ds^2}\right)^2.$$

Therefore

$$Q = \begin{vmatrix} 1 & 0 & -\Sigma\left(\frac{d^2x}{ds^2}\right)^2 \\ 0 & \Sigma\left(\frac{d^2x}{ds^2}\right)^2, & \frac{1}{2}\,d\Sigma\left(\frac{d^2x}{ds^2}\right)^2 \\ -\Sigma\left(\frac{d^2x}{ds^2}\right)^2, & \frac{1}{2}\,d\Sigma\left(\frac{d^2x}{ds^2}\right)^2, & \Sigma\left(\frac{d^3x}{ds^3}\right)^2 \end{vmatrix} = \Sigma\left(\frac{d^2x}{ds^2}\right)^2\Sigma\left(\frac{d^2x}{ds^2}\right)^2 - \Sigma\left(\frac{d^2x}{ds^2}\right)^2.$$

It would not be difficult to find the radius of curvature of the curve at any point by introducing the osculating 3-dimensional sphere and finding its intersection with the osculating 3-flat giving an osculating 2-dimensional sphere. It

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Note on the Theory of Simultaneous Linear Differential or Difference Equations with Constant Coefficients.

By J. J. Sylvester.

This theory is virtually the same for differential as for finite-difference equations. The mere verbal part of the exposition being somewhat easier for the former of the two, I shall prefer in the first instance to deal with them, although the applications are more interesting when made to bear on the latter. Simple to the last degree as are the method of solution and the nature of the result, I do not find the one or the other set out, or even indicated, except in the most perfunctory manner, in the ordinary text-books. This brief notice, designed for the junior readers of the Journal, is intended to supply the lacuna.

Let $u_{j,k}$ denote a linear function, with constant coefficients, of u_k and of its first ε_j derivatives in respect to t.

Let

$$\begin{aligned} u_{1,1} + u_{1,2} + \ldots\ldots + u_{1,\epsilon} &= 0 \\ u_{2,1} + u_{2,2} + \ldots\ldots + u_{2,\epsilon} &= 0 \\ \ldots\ldots\ldots\ldots\ldots\ldots & \\ u_{\epsilon,1} + u_{\epsilon,2} + \ldots\ldots + u_{\epsilon,\epsilon} &= 0 \end{aligned}$$

be the system of differential equations proposed for integration.

Call

$$\varepsilon_1 + \varepsilon_2 + \ldots\ldots + \varepsilon_i = \sigma.$$

The process of arriving at the reducing equation for any one of the variables is after the manner of the dialytic method of elimination, viz.:

Along with the first equation take each of its $(\sigma - \varepsilon_1)^{\text{th}}$ derivatives, with the second equation each of its $(\sigma - \varepsilon_2)^{\text{th}}$ derivatives, . . . and with the i^{th} equation each of its $(\sigma - \varepsilon_i)^{\text{th}}$ derivatives.

There will thus come into existence $(i+1)\sigma - (\varepsilon_1 + \varepsilon_2 \ldots\ldots + \varepsilon_i)$ *i. e.* $i(\sigma+1) - \sigma$ equations between the $i(\sigma+1)$ quantities

$$\begin{aligned} &\omega_1, \quad \delta_t\omega_1, \ldots\ldots \delta_t^{\sigma}\omega_1 \\ &\omega_2, \quad \delta_t\omega_2, \ldots\ldots \delta_t^{\sigma}\omega_2 \\ &\ldots\ldots\ldots\ldots\ldots \\ &\omega_i, \quad \delta_t\omega_i, \ldots\ldots \delta_t^{\sigma}\omega_i \end{aligned}$$

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substitution in the original equations we shall obtain a system of simultaneous algebraical equations leading to the equation

$$\begin{vmatrix} R_{1,1}, & R_{1,2} \ldots . & R_{1,4} \\ R_{2,1}, & R_{2,2} \ldots . & R_{2,4} \\ \ldots\ldots\ldots\ldots\ldots & & \\ R_{4,1}, & R_{4,2} \ldots . & R_{4,4} \end{vmatrix} = 0$$

where in general $R_{p,q}$ is what $u_{p,q}$ becomes on writing h^s in place of $\delta_t^s \omega_q$.

The above determinant of the i^{th} order will be of degree $\varepsilon_1 + \varepsilon_2 \ldots + \varepsilon_i$, *i. e.* of the degree σ (for the general case) in h, and the roots of the equation will give the σ values $h_1, h_2, \ldots h_\sigma$.

It follows, therefore, that the result of the hypothetical elimination in the first instance referred to will be a linear function of $\delta_t^\sigma \omega_k, \delta_t^{\sigma-1} \omega_k, \ldots \delta_t \omega_k, \omega_k$ of which the coefficients will be identical with the coefficients of $h^\sigma, h^{\sigma-1}, \ldots h, 1$ in the above determinant. Hence no matter now what special values may be attributed to the coefficients of the given equations, the result last obtained remains of *universal* validity—without excepting those cases in which the result of the hypothetical elimination would be such that the corresponding algebraical equation possess equal roots, although in those cases the form assumed in the course of the argument for the value of ω_1 (viz. a linear function of exponentials) ceases to hold good. Neither for the same reason need any exception be made for those cases where the number of terms in the equation to ω_k falls below σ on account of one or more of the leading coefficients in the result of the hypothetical elimination becoming zero: the degree to which h rises in the determinant will be in all cases the right degree, whether it reaches the extreme possible limit σ or falls below it.

The result obtained may be briefly summarized as follows.

If
$$\begin{aligned} (\phi_1 \delta_t) x + (\phi_2 \delta_t) y + \ldots\ldots + (\phi_4 \delta_t) z &= 0 \\ (\psi_1 \delta_t) x + (\psi_2 \delta_t) y + \ldots\ldots + (\psi_4 \delta_t) z &= 0 \\ \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots & \\ \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots & \\ (\omega_1 \delta_t) x + (\omega_2 \delta_t) y + \ldots\ldots + (\omega_4 \delta_t) z &= 0 \end{aligned}$$

(each $\phi, \psi, \ldots, \omega$ standing for a rational-integral functional form) then will

$$(R\delta_t) x = 0 \quad (R\delta_t) y = 0 \ldots . (R\delta_t) z = 0,$$

where $R(\delta_t)$ is the resultant in respect to $x, y, \ldots z$ of what the above equations become when δ_t is treated as an ordinary algebraical quantity; under

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which form the proposition (by virtue of Euler's method of multipliers) becomes so nearly intuitive as to abrogate all necessity for any other demonstration.*

To pass to the parallel and more important theory in finite differences, it is only necessary to interpret $u_{j,k}$ to signify a linear function, with constant coefficients, of $(\omega_k)_t$, $(\omega_k)_{t+1}$, . . . $(\omega_k)_{t+j}$, where t is the integer independent variable, (*say* $(\omega_k)_t$ and its ε_j difference-augmentatives), and instead of taking the differential derivatives of any one of the given equations, to take the corresponding difference-augmentatives. Then by precisely the same reasoning as before we shall have

$$\omega_{t+\sigma} + B\omega_{t+\sigma-1} + \ldots + L\omega_t = 0,$$

B, C, . . . L being so taken as that $h^\sigma + Bh^{\sigma-1} + \ldots + L$ shall be the determinant represented by the same form of matrix expressed by R's as before, but where $R_{p,q}$ is obtained from $u_{p,q}$ by writing h^q in lieu of any argument $\omega_t + \theta$ which occurs in it.

The simplest example that can be given is where $i = 2$, $\varepsilon_1 = \varepsilon_2 = 1$,

$$u_{1,1} = -r_{t+1} + ar_t, \qquad u_{1,2} = b\theta_t,$$
$$u_{2,1} = cr_t \qquad\qquad u_{2,2} = -\theta_{t+1} + d\theta_t;$$

this was the case which occurred in the article on the extension of Tchebycheff's theorem, in the last number of the Journal, leading to the equation

$$\begin{vmatrix} a-\lambda & b \\ c & d-\lambda \end{vmatrix} = 0$$

and to expressions for r_t, θ_t as linear functions of λ_1^t, λ_2^t.

It may also be remarked that this same case gives an instantaneous solution of the problem proposed and successfully treated by Babbage in his Calculus of Functions, more than half a century ago, and since revived in connection with the theory of substitutions (Serret, *Alg. Sup.* 4 ed. tom. 2, pp. 256–262). The problem is to find $\phi x = \dfrac{ax+a}{\beta x+b}$ so that $\phi^i x$, say $\dfrac{a_i x + a_i}{\beta_i x + b_i}$, shall equal x for a given value of i.

To find in general $\phi^t x$ it is only necessary to solve the difference equations

$$u_t = au_{t-1} + \alpha v_{t-1}$$
$$v_t = \beta u_{t-1} + bv_{t-1},$$

and then u_t, v_t will, if $u_0 = 1$, $v_0 = 0$, coincide with a_t, β_t, and if $u_0 = 0$, $v_0 = 1$ with α_t, b_t.

* I regret that this simple reflection did not present itself to my mind before the preceding investigation, the necessity for which it does away with, had been set up in print. It of course applies equally well to the analogous proposition for finite-difference equations (u, v, ... being substituted for x, y . . . . , and $1 + \Delta$ for δ.). This last named proposition, limited to the case of equations of the first order, is the foundation-stone of my new theory of Matrices regarded as Quantities, *i. e.* as subject to every kind of functional operation which ordinary arithmetical or algebraical quantities are or can be subject to: but though so important and so easily established, I know not where it can be found explicitly stated.

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Thus calling ρ_1, ρ_2 the two roots of

$$\begin{vmatrix} -\rho + a & \alpha \\ \beta & -\rho + b \end{vmatrix} = 0,$$

a_i will be of the form $C(\rho_1^i - \rho_2^i)$ and β_i of the same form except as to C, say $\Gamma(\rho_1^i - \rho_2^i)$. Also a_i, b_i will be of the forms $C_1\rho_1^i + C_2\rho_2^i$, $\Gamma_1\rho_1^i + \Gamma_2\rho_2^i$, where $C_1 + C_2 = 1$, $\Gamma_1 + \Gamma_2 = 1$, and the required condition will be fulfilled, provided only that $\rho_1^i = \rho_2^i$, or say

$$\rho_1 = K\left(\cos\frac{\lambda\pi}{i} + \sqrt{-1}\,\sin\frac{\lambda\pi}{i}\right)$$

$$\rho_2 = K\left(\cos\frac{\lambda\pi}{i} - \sqrt{-1}\,\sin\frac{\lambda\pi}{i}\right)$$

i. e. if $(a+b)^2 - 4(ab - \alpha\beta)\left(\cos\frac{\lambda\pi}{i}\right)^2 = 1$, λ having any integer value (which without loss of generality may be taken inferior to i) except zero.*

If $\lambda = 0$, the two roots of the equation in ρ become equal and the form of the solution changes into

$$u_i = (C_1 + C_2 i)\rho^i \qquad v_i = (C_1' + C_2' i)\rho^i.$$

When $u_0 = 1$ and $v_0 = 0$ then $u_1 = a$, $v_0 = \beta$,

$$C_1 = 1,\ C_1' = 0, \qquad C_2 = \frac{a}{\rho} - 1,\ C_2' = \frac{\beta}{\rho},$$

and when $u_0 = 0$, $v_0 = 1$, $u_1 = \alpha$, $v_0 = b$,

$$C_1 = \frac{a}{\rho},\ C' = \frac{b}{\rho} - 1, \qquad C_2 = 0,\ C_1' = 1,$$

and $\phi^i x = \dfrac{[\rho + i(a-\rho)]\,x + i\,a}{i\beta x + \rho + (b-\rho)\,i}$ which cannot be periodic for any value of i, and when $i = \infty$ becomes $\dfrac{(a-\rho)\,x + a}{\beta x + b - \rho} = \dfrac{a-\rho}{\beta} = \dfrac{a}{b-\rho}$, *i. e.* $= \dfrac{a-b}{2\beta}$ or $\dfrac{2a}{a-b}$, so that $\phi^i x$ in this case continually converges to a constant limit.

I may add that $\phi^i x$ converges to a constant limit not merely when the roots ρ_1, ρ_2 of

$$\begin{vmatrix} a-\rho & \alpha \\ \beta & b-\rho \end{vmatrix}$$

are equal, but whenever they are real. For the general form of $\phi^i x$, it may easily be found, is

$$\frac{[(\rho_2 - a)\,\rho_1^i + (\rho_1 - a)\,\rho_2^i]\,x + a(\rho_1^i - \rho_2^i)}{\beta(\rho_1^i - \rho_2^i)\,x + [(\rho_2 - b)\,\rho_1^i + (\rho_1 - b)\,\rho_2^i]}$$

* There will thus be $(i-1)$ values of λ which will each give a distinct admissible solution of the problem of periodicity, but of course only those values of λ which are relatively prime to i will give primitive solutions. If $i = i'\delta$ the effect of making $\lambda = \lambda'\delta$ will be to make $\phi^i x = x$ by virtue of its making $\phi^{i'} x = 0$.

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which if $\rho_2 > \rho_1$ when $i = \infty$ becomes $\frac{(\rho_1 - a)x - a}{-\beta x + \rho_1 - b} = \frac{a - \rho_1}{\beta}$ or $\frac{a}{b - \rho_1}$ where ρ_1 signifies the smaller of the two roots ρ_1, ρ_2; or in other words when $a - b > 2\sqrt{\alpha\beta}$, the limiting value to $\phi^i x$, when ϕx represents $\frac{\alpha x + a}{\beta x + b}$, is $\frac{(a-b) + \sqrt{(a-b)^2 - 4\alpha\beta}}{2\beta}$, with the understanding that the quantity under the radical sign is to be taken positive.

So, if

$x_{i+1} : y_{i+1} : z_{i+1} = ax_i + by_i + cz_i : a'x_i + b'y_i + c'z_i : a''x_i + b''y_i + c''z_i$,

when all the roots of the determinant

$$\begin{vmatrix} a - \lambda & b & c \\ a' & b' - \lambda & c' \\ a'' & b'' & c'' - \lambda \end{vmatrix}$$

are real, the point x_i, y_i, z_i, as i increases, will be found to approach indefinitely near to a fixed straight line; and if all the roots are equal, to a fixed point.

The condition of the system of ratios $x_i : y_i : z_i$ being periodic and having a period m is tantamount to the condition that the m^{th} power of the matrix

$$\begin{matrix} a & b & c \\ a' & b' & c' \\ a'' & b'' & c'' \end{matrix}$$

shall be the matrix

$$\begin{matrix} 1 & 0 & 0 \\ 0 & 1 & 0 \\ 0 & 0 & 1 \end{matrix}.$$

The complete solution of this problem, and of the more general one of extracting the m^{th} root of any unit-matrix (*i. e.* a matrix in which each element in the principal diagonal is unity, and the rest zero), which constitutes the ultimate generalization of Babbage's problem and is soluble by the same method, will probably appear in a memoir on matrices, in the forthcoming number of the Journal.

In general, for a matrix of the order ω, the number of m^{th} roots is m^ω and each of them is perfectly determinate. But when the matrix is a unit-matrix or a zero-matrix (the latter meaning one in which every element is zero) there are distinct genera and species of such roots, and every species contains its own appropriate number of arbitrary constants.

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Alhazen's Problem.

Its Bibliography and an Extension of the Problem.

By Marcus Baker.

Problem. *From two points in the plane of a circle, to draw lines meeting at a point in the circumference and making equal angles with the tangent drawn at that point.*

This problem is known as Alhazen's, and has been studied by several mathematicians, besides Alhazen, from the time of Huyghens to the present. The earliest solutions are all geometrical constructions in which the points are determined by the intersections of a hyperbola with the given circle. Later, analytical solutions were given, and lastly trigonometrical solutions.

The following list of references and their accompanying notes contains a condensed history of the problem.

Alhazen. Opticae thesavrvs Alhazeni arabis libri septem nunc primùm editi . . . à Risnero. 4 p.l. 288 pp. fol. *Basileae per episcopios* MDLXXII.

Alhazen was an Arabian who lived in the 11th century of the Christian era, dying at Cairo in 1038. He wrote this treatise on optics, which was first published, as above stated, in 1572, under the editorship of Risner. The first published solution of the problem is contained in this book, pp. 144–148, Props. 34, 38 and 39. The solution is effected by the aid of a hyperbola intersecting a circle, and is excessively prolix and intricate.

Analyst (The). A journal of pure and applied mathematics. Edited and published by J. E. Hendricks, A. M. 8vo. *Des Moines, Iowa: Mills & Co.* 1877. Vol. IV, No. 3, pp. 124–125.

A general solution was proposed, but the solution of only a special case was published.

Barrow (*Rev.* Isaac, *D. D.*) Lectiones xviii Cantabrigiae in scholis publicis habitae in qvibvs opticorum phaenomenΩn genuinae rationes investigantur, ac exponuntur. 8vo. *Londini, typis Gulielmi Godbid*, 1669. Lect. ix.

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See also WHEWELL'S edition of Barrow's works. 8vo. *Cambridge, University Press*, 1860. Lectiones opticae, pp. 84–89.

Barrow refers to Alhazen's "horribly prolix" solution, and discusses some of its special cases as applied to optics.

HUTTON (*Dr.* Charles). Trigonometrical solution of Alhazen's problem.

[*In* LEYBOURN (Thomas). The mathematical questions proposed in the Ladies' Diary (etc.) 8vo. *London: J. Mawman*, 1817. Vol. I, pp. 167–168.]

A trigonometrical solution by trial and error.

HUYGHENS (Christian) and SLUSE (Francis Rene). Excerpta ex epistolis nonnullis (etc.)

[*In* PHILOSOPHICAL TRANSACTIONS of the Royal Society. 4to. *London*, 1673. Vol. VIII, pp. 6119–6126, 6140–6146.]

Several solutions are contained in this correspondence, all of them geometrical, and all except one being by the aid of an hyperbola. One solution, by Sluse, is by means of the intersection of a parabola with the given circle. One of the solutions by Huyghens is the most elegant the problem has ever received.

KAESTNER (Abraham Gotthelf). Problematis Alhazeni analysis trigonometrica.

[*In* NOVI COMMENTARII societatis regiae scientiarum GOTTINGENSIS tomus VII, 1776. 4to. *Gottingae, J. C. Dieterich*, 1777, pp. 92–141. 1 pl.]

A complete trigonometrical solution, with application to several numerical examples, and containing differential equations to facilitate the computation.

LADIES' DIARY. 16mo. *London*, 1727. *Not seen.*

The problem concretely stated was the prize problem in the Diary for 1727. Solved the following year by trial and error by I . . . T . . .

LEYBOURN (Thomas). Geometrical construction of Alhazen's problem.

[*In* LEYBOURN (Thomas). The mathematical questions proposed in the Ladies' Diary (etc.) 8vo. *London: J. Mawman*, 1817. Vol. I, pp. 168–169.]

This construction is arranged from old material. The proof is given clearly and concisely, and a few bibliographic indications are added.

L'HOSPITAL (Guillaume François Antoine de). Traité analytique de sections coniques. 4to. *Paris: Montalant*, 1720. Livre X, Ex. vii, pp. 389–395.

In Book X, on determinate sections, Alhazen's problem is selected as an example of a problem whose geometrical solution can be effected by the aid of a conic section. Two solutions are given, essentially the same as those by Huyghens and Sluse, but with improved methods of arrangement and proof.

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MAYER (Tobias). In a collection of problems by Mayer there is said to be a solution of Alhazen's problem. *Not seen.*

PHILOSOPHICAL TRANSACTIONS. *See* HUYGHENS and WALES.

PRIESTLY (Joseph). History of optics, translated into German with notes by Simon Klügel. 2 vols. Leipzig, 1775–6. *Not seen.*

Said to contain information about Alhazen's problem.

RISNER (Frederic)—Editor. *See* ALHAZEN.

ROBINS (Benjamin). Mathematical tracts. 2 vols. 8vo. *London*, 1761. *See* Vol. II, pp. 262–264.

One of these tracts is a scathing review of Robert Smith's "compleat system of optics." Robins points out the complete omission of Alhazen's problem, and supplies a short and easy proof of the correctness of one of Sluse's solutions.

SEITZ (Enoch Beery). Solution of a problem.

[*In* SCHOOL (The) VISITOR, devoted to the study of mathematics and grammar. 8vo. *Ansonia, Ohio: John S. Royer*, 1881. Vol. II, No. 2, February, pp. 24–25.]

A complete algebraical solution by an equation of the eighth degree, with numerical application and roots found by Horner's method.

SIMSON (Robert). Said to have solved the problem, but no solution is contained in any of his works accessible to the author.

SLUSE (Francis Rene). *See* HUYGHENS and SLUSE.

T . . . (I . . .). *See* LADIES' DIARY.

WALES (William). On the resolution of adfected equations.

[*In* PHILOSOPHICAL TRANSACTIONS of the Royal Society. 4to. *London*, 1781. Vol. LXXI, part 1, Ex. vi, pp. 472–476.]

Alhazen's problem is selected as furnishing an example of an adfected quadratic equation whose solution is easily effected by the aid of the logarithmic tables and his method of using them.

Alhazen's Problem extended to the Surface of a Sphere.

The solution of Alhazen's problem gives the minimum (and also maximum) path between two points and an intermediary circle, the points and circle being situated in the same plane, and we shall here give the solution of the same problem when the two points and circumference of the given circle are situated in the surface of a sphere.

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To find the great circle distance between two places on the earth's surface, and the azimuth of the great circle at each place.

Let A be the place in latitude $= \alpha$, and longitude λ_1,
and B " " " " $= \alpha_1$ " " λ_2.

The shortest distance between two points on the surface of the sphere is always an arc of the great circle joining them. Suppose this great circle passes through a given position of the point P when $\theta = 0$. We wish to find the minimum value between A and B as the spherical surface with lines on it passes round the axis of latitude θ.

The shortest path between two points of great circle arcs drawn from A and B to a point P at latitude θ is when it makes equal angles with the parallel of P. The problem is to find the point P.

Referring to the annexed figure, let us find a minimum value for λ when P is within the triangle. Let $OA = x$, $OB = y$, and $OP = z$; then

$$\tan APM = \frac{\sin z}{\sin x - \sin z}, \text{ and } \tan BPN = \frac{\sin y}{\sin y - \sin z}.$$

and as these angles are equal we have

$$\frac{\sin z}{\sin x - \sin z} = \frac{\sin y}{\sin y - \sin z}.$$

in which $x - y = \alpha$ a known angle. Replacing y by $x - \alpha$, we have a convenient formula for solving by approximation.

The solution for the extended problem is analogous to the foregoing. O is the point of the sphere, A and B the given points, and P the point sought. OA, OB and OM are arcs of great circles, as are also PA and PB, and AM and BN are arcs of great circles perpendicular to OP. Let $AOM = x$, $BOM = y$, and $OP = \theta - \phi$.

Then
$$\sin AM = \sin AO \sin x,$$
$$\sin BN = \sin BO \sin y,$$

and
$$\tan OM = \tan AO \cos x,$$
$$\tan ON = \tan BO \cos y;$$

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also $$\tan APM = \tan BPM \quad \text{or} \quad \frac{\tan AM}{\sin PM} = \frac{\tan BN}{\sin PN}$$

whence $$\frac{\tan^2 AM}{\tan^2 BN} = \frac{\sin^2 PM}{\sin^2 PN}. \tag{1}$$

Now $$\frac{\tan^2 AM}{\tan^2 BN} = \frac{\sin^2 AM \cos^2 BN}{\cos^2 AM \sin^2 BN} = \frac{\sin^2 AO \sin^2 x (1 - \sin^2 BO \sin^2 y)}{(1 - \sin^2 AO \sin^2 x) \sin^2 BO \sin^2 y}; \tag{2}$$

and again, since $PN = ON - OP$ and $PM = OM - OP$,

$$\frac{\sin^2 PM}{\sin^2 PN} = \left\{ \frac{\sin OM \sin\varphi - \cos OM \cos\varphi}{\sin ON \sin\varphi - \cos ON \cos\varphi} \right\}^2 = \frac{\cos^2 OM}{\cos^2 ON} \left\{ \frac{\tan OM \sin\varphi - \cos\varphi}{\tan ON \sin\varphi - \cos\varphi} \right\}^2.$$

But $$\frac{\cos^2 OM}{\cos^2 ON} = \frac{1 + \tan^2 ON}{1 + \tan^2 OM} = \frac{1 + \tan^2 BO \cos^2 y}{1 + \tan^2 AO \cos^2 x},$$

whence $$\frac{\sin^2 PM}{\sin^2 PN} = \left\{ \frac{1 + \tan^2 BO \cos^2 y}{1 + \tan^2 AO \cos^2 x} \right\} \cdot \left\{ \frac{\tan AO \cos x \sin\varphi - \cos\varphi}{\tan BO \cos y \sin\varphi - \cos\varphi} \right\}^2. \tag{3}$$

Substituting (2) and (3) in (1), and remembering that

$$AO = 90° - \phi_1 \quad \text{and} \quad BO = 90° - \phi_2$$

we obtain

$$\frac{\cos^2\varphi_1 \sin^2 x (1 - \cos^2\varphi_2 \sin^2 y)}{(1 - \cos^2\varphi_1 \sin^2 x) \cos^2\varphi_2 \sin^2 y} = \left\{ \frac{1 + \operatorname{cotg}^2\varphi_2 \cos^2 y}{1 + \operatorname{cotg}^2\varphi_1 \cos^2 x} \right\} \cdot \left\{ \frac{\operatorname{cotg}\varphi_1 \sin\varphi \cos x - \cos\varphi}{\operatorname{cotg}\varphi_2 \sin\varphi \cos y - \cos\varphi} \right\}^2,$$

or

$$\frac{\cos^2\varphi_1 \sin^2 x (1 - \cos^2\varphi_2 \sin^2 y)(1 + \operatorname{cotg}^2\varphi_1 \cos^2 x)(\operatorname{cotg}\varphi_2 \cos y - \operatorname{cotg}\varphi)^2}{\cos^2\varphi_2 \sin^2 y (1 - \cos^2\varphi_1 \sin^2 x)(1 + \operatorname{cotg}^2\varphi_2 \cos^2 y)(\operatorname{cotg}\varphi_1 \cos x - \operatorname{cotg}\varphi)^2} = 1.$$

Now $x + y = \lambda_2 - \lambda_1 = \Delta\lambda$, whence eliminating x or y we have an equation which can be solved by approximation as in the case of a plane surface.

WASHINGTON, D. C., *October* 26, 1881.

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On the Non-Euclidean Trigonometry.

By William E. Story.

In the "Sixth memoir upon quantics" * Professor Cayley has given a projective definition of geometrical quantity of one dimension. Distance between two points and angle between two lines, which has been generalized by Dr. Klein in a paper "Ueber die sogenannte Nicht-Euklidische Geometrie." † Professor Cayley afterwards gave an example of the non-Euclidean trigonometry in the plane, obtaining the formulæ for the special case in which the fundamental conic or "absolute" is a circle, and the constants of measurement have particular values. ‡ I propose here to deduce the formulæ for the general case of projective measurement in the plane with an arbitrary absolute and arbitrary constants. The application of the results to a space of two dimensions with constant curvature in a third dimension is evident. It is also evident from the nature of the projective measurement that the results are independent of the particular choice of coördinates, and therefore are not affected by the circumstance that a real point may have imaginary coördinates.

Following Professor Cayley's notation, I put a dash over any quantity measured projectively. The projective measure $\bar{a}$ of the distance between two points B and C, and the projective measure $\bar{A}$ of the angle between two lines b and c, are defined thus:

$$\bar{a} = k \ln \alpha, \quad \bar{A} = k' \ln \alpha',$$

where α is the anharmonic ratio of B and C with respect to the intersections of the line BC with the absolute, and α' is the anharmonic ratio of b and c with

* Philosophical Transactions, Vol. 149, 1859. † Mathematische Annalen, Vol. IV, pp. 573–625.
‡ Mathematische Annalen, Vol. V, pp. 630–634.

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respect to the tangents from the point bc to the absolute, and k and k' are two arbitrary constants corresponding to the arbitrary units of ordinary linear and angular measurement.

Let the equations of the absolute in point-coördinates x, y, z, and in tangential coördinates u, v, w, be

$$\Omega \equiv f(x, y, z) = 0 \quad \text{and} \quad \mathfrak{V} \equiv F(u, v, w) = 0,$$

respectively; and let

$$\Omega_{11} \equiv f(x_1, y_1, z_1), \qquad \Omega_{12} \equiv \frac{1}{2}\left[x_1 \frac{\partial \Omega_{22}}{\partial x_2} + y_1 \frac{\partial \Omega_{22}}{\partial y_2} + z_1 \frac{\partial \Omega_{22}}{\partial z_2}\right],$$

$$\mathfrak{V}_{11} \equiv F(u_1, v_1, w_1), \quad \mathfrak{V}_{12} \equiv \frac{1}{2}\left[u_1 \frac{\partial \mathfrak{V}_{22}}{\partial u_2} + v_1 \frac{\partial \mathfrak{V}_{22}}{\partial v_2} + w_1 \frac{\partial \mathfrak{V}_{22}}{\partial w_2}\right],$$

and similarly for other combinations of the suffices 1, 2, 3.

Let A, B, C be the vertices of a triangle, a, b, c their sides, $\overline{A}$, $\overline{B}$, $\overline{C}$, $\overline{a}$, $\overline{b}$, $\overline{c}$ the projective measures of the angles and opposite sides, respectively; and let the coördinates of A, B, C, a, b, c, be x_1, y_1, z_1; x_2, y_2, z_2; x_3, y_3, z_3; u_1, v_1, w_1; u_2, v_2, w_2; u_3, v_3, w_3, respectively. Then, by the above definitions,

$$\bar{a} = k \ln \frac{\Omega_{23} + \sqrt{\Omega_{23}^2 - \Omega_{22}\Omega_{33}}}{\Omega_{23} - \sqrt{\Omega_{23}^2 - \Omega_{22}\Omega_{33}}},$$

$$\overline{A} = k' \ln \frac{\mathfrak{V}_{23} + \sqrt{\mathfrak{V}_{23}^2 - \mathfrak{V}_{22}\mathfrak{V}_{33}}}{\mathfrak{V}_{23} - \sqrt{\mathfrak{V}_{23}^2 - \mathfrak{V}_{22}\mathfrak{V}_{33}}},$$

which can be put into the forms

$$\bar{a} = 2ik \cos^{(-1)} \frac{\Omega_{23}}{\sqrt{\Omega_{22}\Omega_{33}}}, \quad \overline{A} = 2ik' \cos^{(-1)} \frac{\mathfrak{V}_{23}}{\sqrt{\mathfrak{V}_{22}\mathfrak{V}_{33}}},$$

i. e.

$$\cos\left(\frac{\bar{a}}{2ik}\right) = \frac{\Omega_{23}}{\sqrt{\Omega_{22}\Omega_{33}}}, \quad \cos\left(\frac{\overline{A}}{2ik'}\right) = \frac{\mathfrak{V}_{23}}{\sqrt{\mathfrak{V}_{22}\mathfrak{V}_{33}}}.$$

For convenience I take for the lines $x = 0$, $y = 0$, $z = 0$ respectively two conjugate polars through the point A and the polar of A with respect to Ω, so that

$$\Omega \equiv x^2 + y^2 + z^2, \text{ and hence } \mathfrak{V} \equiv u^2 + v^2 + w^2,$$

$$\Omega_{23} \equiv x_2x_3 + y_2y_3 + z_2z_3, \quad \mathfrak{V}_{23} \equiv u_2u_3 + v_2v_3 + w_2w_3,$$

$$x_1 : y_1 : z_1 = 0 : 0 : 1,$$

$$u_2 : v_2 : w_2 = y_3 : -x_3 : 0, \quad u_3 : v_3 : w_3 = y_2 : -x_2 : 0;$$

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and, putting $x_2 = z_2 r_2 \cos\phi_2$, $y_2 = z_2 r_2 \sin\phi_2$, $x_3 = z_3 r_3 \cos\phi_3$, $y_3 = z_3 r_3 \sin\phi_3$, I find

$$\Omega_{11} = 1\,,\ \Omega_{22} = z_2^2(r_2^2+1)\,,\ \Omega_{33} = z_3^2(r_3^2+1)\,,$$
$$\Omega_{12} = z_2\,,\ \Omega_{13} = z_3\,,\ \Omega_{23} = z_2 z_3\,[r_2 r_3 \cos(\phi_3-\phi_2)+1]\,,$$
$$\mathfrak{U}_{22} = z_2^2 r_2^2\,,\ \mathfrak{U}_{33} = z_3^2 r_3^2\,,\ \mathfrak{U}_{23} = z_2 z_3 r_2 r_3 \cos(\phi_3-\phi_2)\,,$$

$$\cos\left(\frac{\bar a}{2ik}\right) = \pm\frac{1+r_2 r_3\cos(\varphi_3-\varphi_2)}{\sqrt{(r_2^2+1)(r_3^2+1)}}\,,\quad \cos\left(\frac{\bar A}{2ik}\right) = \pm\cos(\phi_3-\phi_2)\,,$$

$$\cos\left(\frac{\bar b}{2ik}\right) = \frac{\pm 1}{\sqrt{r_3^2+1}}\,,\quad \sin\left(\frac{\bar b}{2ik}\right) = \frac{\pm r_3}{\sqrt{r_3^2+1}}\,,$$

$$\cos\left(\frac{\bar c}{2ik}\right) = \frac{\pm 1}{\sqrt{r_2^2+1}}\,,\quad \sin\left(\frac{\bar c}{2ik}\right) = \frac{\pm r_2}{\sqrt{r_2^2+1}}\,,$$

$$\cos\left(\frac{\bar a}{2ik}\right) = \pm\cos\left(\frac{\bar b}{2ik}\right)\cos\left(\frac{\bar c}{2ik}\right) \pm \sin\left(\frac{\bar b}{2ik}\right)\sin\left(\frac{\bar c}{2ik}\right)\cos\left(\frac{\bar A}{2ik}\right),$$

where each sign $\pm$ has to be so determined that the distance between two coincident points and the angle between two coincident lines shall be 0, or some multiple of the whole length of a straight line and whole angle about a point respectively, while it remains arbitrary in which of the two possible directions the measure is positive. If the points B and C coincide, $\bar c = \bar b$, $\bar a = 0$, $\bar A = 0$, hence, by the last formula,

$$1 = \pm\cos^2\left(\frac{\bar b}{2ik}\right) \pm \sin^2\left(\frac{\bar b}{2ik}\right),$$

therefore the upper sign is to be given to both terms, *i. e.*

$$\cos\left(\frac{\bar a}{2ik}\right) = \cos\left(\frac{\bar b}{2ik}\right)\cos\left(\frac{\bar c}{2ik}\right) + \sin\left(\frac{\bar b}{2ik}\right)\sin\left(\frac{\bar c}{2ik}\right)\cos\left(\frac{A}{2ik'}\right),$$

corresponding to the formula of spherical trigonometry

$$\cos a = \cos b\cos c + \sin b\sin c\cos A\,,$$

from which, as is well known, all the other formulae of spherical trigonometry can be obtained, without the use of any other relations than those implied in the definitions of the trigonometric functions. Hence, in a uniformly curved space of two dimensions, with a projective measurement based upon any conic, whose constants of linear and angular measurement are k and k' respectively, *the trigonometrical formulae will be obtained from those of spherical trigonometry by replacing each side* (*or arc*) *by the corresponding side* (*or straight line*) *divided by*

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$2ik$, *and each angle by the corresponding angle divided by* $2ik'$. Of course, what we call a straight line in such a curved space is a geodesic line, *i. e.* the shortest line between any two of its points measured as above.

If $k = \frac{1}{2}$, $k' = \frac{1}{2i}$,

then
$$\frac{\bar{a}}{2ik} = -i\bar{a}, \quad \frac{\bar{A}}{2ik'} = \bar{A},$$

$$\sin\left(\frac{\bar{a}}{2ik}\right) = -i\sinh\bar{a}, \quad \cos\left(\frac{\bar{a}}{2ik}\right) = \cosh\bar{a},$$

whence
$$\cos\bar{A} = -\frac{\cosh\bar{a} - \cosh\bar{b}\cosh\bar{c}}{\sinh\bar{b}\sinh\bar{c}},$$

the formula given by Professor Cayley, which, however, holds for any other fundamental conic, as well as for a circle.

BALTIMORE, *March* 28, 1882.

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Note on Mechanical Involution.

By J. J. Sylvester.

Mechanical involution is the name invented by me to signify the relation between six lines in space, so situated that forces may be made to act along them whose statical sum is zero. The definition may be extended to comprise an indefinite number of lines, any six of which have this property.

I shall use $[p, q]$ for the present to denote the moment of a unit of force acting along the directed line p about the directed line q, taken positive or negative according as to a spectator looking in the given direction (or sense) of q, a force in the given direction (or sense) of p tends to produce a right-handed or a left-handed rotation, which tendency, by a property of our mental constitution, we know is not affected in kind by the lines p and q becoming interchanged—a fact which might also be anticipated with a high degree of probability from the circumstance that the unit-moment is measured by the product of the perpendicular distance from each other, of the two lines, multiplied by the sine of the angle between them, so that *each* factor of this product changes its sign when the relation or aspect of the two lines to each other is reversed. Hence it follows that $[p, q] = [q, p]$.

Three lines in a plane, it may be noticed, are in involution when they intersect in the same point, or, as a particular case, are parallel to each other.

Let a, b, c, d, e, f be any six lines in space, $\lambda_1, \lambda_2, \lambda_3, \lambda_4, \lambda_5, \lambda_6$ six forces capable of balancing when acting along the lines 1, 2, 3, 4, 5, 6 supposed to be in involution.

Then by the equation of moments in regard to each of the first series of lines taken successively as axes of rotation, we must have

$$\lambda_1[1, a] + \lambda_2[2, a] + \lambda_3[3, a] + \lambda_4[4, a] + \lambda_5[5, a] + \lambda_6[6, a] = 0$$
$$\lambda_1[1, b] + \ldots\ldots\ldots\ldots\ldots\ldots + \lambda_6[6, b] = 0$$
$$\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots$$
$$\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots$$
$$\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots$$
$$\lambda_1[1, f] + \lambda_2[2, f] + \lambda_3[3, f] + \lambda_4[4, f] + \lambda_5[5, f] + \lambda_6[6, f] = 0$$

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and consequently the determinant

$$\begin{vmatrix} [1, a] & \cdots & [6, a] \\ \cdots & \cdots & \cdots \\ \cdots & \cdots & \cdots \\ \cdots & \cdots & \cdots \\ \cdots & \cdots & \cdots \\ [1, f] & \cdots & [6, f] \end{vmatrix} = 0.$$

Consequently we may find quantities μ_a, μ_b, μ_c, μ_d, μ_e, μ_f such that

$$\mu_a[a, 1] + \mu_b[b, 1] + \mu_c[c, 1] + \mu_d[d, 1] + \mu_e[e, 1] + \mu_f[f, 1] = 0$$
$$\cdots\cdots\cdots\cdots\cdots\cdots$$
$$\cdots\cdots\cdots\cdots\cdots\cdots$$
$$\cdots\cdots\cdots\cdots\cdots\cdots$$
$$\cdots\cdots\cdots\cdots\cdots\cdots$$
$$\mu_a[a, 6] + \mu_b[b, 6] + \mu_c[c, 6] + \mu_d[d, 6] + \mu_e[e, 6] + \mu_f[f, 6] = 0.$$

Thus it becomes evident by regarding μ_a, μ_b, μ_c, μ_d, μ_e, μ_f as the magnitudes of forces acting along the lines a, b, c, d, e, f, that the equations of moments of a given set of forces about six lines which are in general independent, become linearly related when the six axes are in involution—a conclusion which springs also immediately from the consideration that the law of statical composition of directed lengths is the same whether they be regarded as representing forces or as representing the axes of couples. So much by way of introduction.

I now pass to the formation of the intrinsic equation of condition to be satisfied in the case of involution.

To obtain this, let the lines a, b, c, d, e, f be made identical with 1, 2, 3, 4, 5, 6.

In each of these latter lines (say in i) let two points be taken at the distance $\frac{1}{i_t}$ apart, whose quadriplanar coördinates are respectively i_x, i_y, i_z, i_t, i'_x, i'_y, i'_z, i'_t, and let (i, j)—where j is another of the lines in involution—denote the determinant

$$\begin{vmatrix} i_x & i_y & i_z & i_t \\ i'_x & i'_y & i'_z & i'_t \\ j_x & j_y & j_z & j_t \\ j'_x & j'_y & j'_z & j'_t \end{vmatrix}$$

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The determinant will represent a charged distribution of a certain type of which case the charge between the points of points on i, j respectively and k, l respectively $= l_{ij}\, l_{kl}$ — same to represent in the same way, the l_{ij} which in general may be represented by l_{ij}.

Hence the determinant of the same order above written becomes

$$\begin{array}{cccccc} 0 & l_{12}\,l_{21} & l_{13}\,l_{31} & l_{14}\,l_{41} & l_{15}\,l_{51} & l_{16}\,l_{61} \\ l_{21}\,l_{12} & 0 & l_{23}\,l_{32} & l_{24}\,l_{42} & l_{25}\,l_{52} & l_{26}\,l_{62} \\ \cdots & \cdots & \cdots & \cdots & \cdots & \cdots \\ \cdots & \cdots & \cdots & \cdots & \cdots & \cdots \\ \cdots & \cdots & \cdots & \cdots & \cdots & \cdots \\ l_{61}\,l_{16} & l_{62}\,l_{26} & l_{63}\,l_{36} & l_{64}\,l_{46} & l_{65}\,l_{56} & 0 \end{array}$$

and this equated to zero gives the intrinsic condition of involution.

Imagining this equation to be formed, the terms in each line and also the terms in each column will have some common factor remaining which by a two-fold scheme of division all the quantities l will disappear, so that now regarding each of the pairs of points on the lines 1, 2, 3, 4, 5, 6 respectively as *any two non-coincident points whatever*, the intrinsic condition is represented by the evanescence of the following symmetrical invertebrate (i. e. zero-axial) compound determinant

0	(1, 2)	(1, 3)	(1, 4)	(1, 5)	(1, 6)
(2, 1)	**0**	(2, 3)	(2, 4)	(2, 5)	(2, 6)
(3, 1)	(3, 2)	**0**	(3, 4)	(3, 5)	(3, 6)
(4, 1)	(4, 2)	(4, 3)	**0**	(4, 5)	(4, 6)
(5, 1)	(5, 2)	(5, 3)	(5, 4)	**0**	(5, 6)
(6, 1)	(6, 2)	(6, 3)	(6, 4)	(6, 5)	**0**

where each pair of numbers within a parenthesis represents a determinant of the fourth order.*

Just as the equations of moments of a system of forces about six lines in space are in general independent, but cease to be so if (and only if) these lines are in involution, so the equations of moments of a system of forces in a plane about three points are in general independent, and only cease to be so when the three points lie in a right line. Thus under the two-fold aspect of a system of force-directions and a system of axes of moments, six lines in involution in space are on the one hand the analogues of three force-directions in a plane in

* This determinant (which is sufficiently obvious, I have found since going to press) has been given by Prof. Cayley in his memoir on line-coordinates, Cam. Phil. Trans., 1861, which is avowedly based upon my constructions connected with the problem of Involution.

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involution, *i. e.* meeting in a point, and on the other hand of three points (centres of moments) lying in a right line; and as *concurrence* is the polar correlative to *collineation* we ought to expect to find involution in space to be its own polar correlative; *i. e.* that the polar reciprocal of a system of lines in involution in respect to a general quadric should be another such system: and such is the fact: for, as I have shown in the *Comptes Rendus*, the necessary and sufficient condition of six lines being in involution is that they shall respectively intersect pairs of corresponding rays in two homographic pencils lying in two planes whose intersection contains the centres and two corresponding (coincident) rays of the two pencils—a condition which will not be affected by any polar transformation.

This leads to the remark that we may change the signification of the symbol (i, j) in the equation last indicated without destroying its validity as the condition of involution: viz. we may suppose two planes to be drawn through each line instead of two points being fixed upon it: and then if we understand by the determinant of two lines in space the determinant formed by the coefficients of the two pairs of equations which denote the lines, we may interpret (i, j) to mean the determinant of i, j and sum up the result obtained in the following proposition:

The determinants formed by six lines in involution, taken two and two together, are related in precisely the same manner as the squared distances from one another of six points in four-dimensional space.

The legitimacy of the second reading of (i, j) may be proved directly, as follows. For greater clearness let (i, j) when read with reference to pairs of planes through i and j, be called (I, J). Then

$$\begin{matrix} i_x & i_y & i_z & i_t \\ i'_x & i'_y & i'_z & i'_t \\ I_x & I_y & I_z & I_t \\ I'_x & I'_y & I'_z & I'_t \end{matrix}$$

will constitute an example of what in the Johns Hopkins University Circular for May, 1882,* I have called a *split matrix*, inasmuch as each of the first two

* Baltimore: John Murphy & Co.—It is interesting to notice (as there indicated) that the same theory of the split matrix here applied to mechanical involution has an important, although quite a different kind of bearing on the theory of algebraical involution. The two theories of involution have a considerable affinity to each other—groundforms and their coefficients in the equation of linear connection in the one theory, being regarded as the analogues of space-directions and the force-magnitudes acting along them in the other. (See J. H. U. Circular, June, 1882.) It was the sense of this connection which caused me to throw a retrospective glance on the theory of mechanical involution, abandoned by me since the remote date of the appearance of my papers on the subject in the *Comptes Rendus*. I ought to mention that I owe the idea of applying the split-matrix theory to the proof of the polar property of an involution-system, to a suggestion of Professor Cayley.

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each unit pair and then by each of the latter two gives products whose sum is zero. Hence by virtue of the property of such a matrix each complete set of the eight pairs will lead to the opposite complete unity in the answer just the ratio of I_0 to I_1, where

$$I^0 = \begin{matrix} \Sigma P_0^2 & \Sigma P_0 P_1 \\ \Sigma P_0 P_1 & \Sigma P_1^2 \end{matrix} \quad \text{and} \quad I^1 = \begin{matrix} \Sigma P_0 & \Sigma P_0 P_1 \\ \Sigma P_0 P_1 & \Sigma P_1^2 \end{matrix},$$

and of course the same considerations apply word for word when i, I take the place of i, I; from which it immediately follows that

$$(i, j; I, J) = (i, j; I, J).$$

Let now in the (i, j) determinant which is equated to zero, each element in any θ^{th} column be multiplied by $\frac{I_\theta}{I_0}$, and then again each element in any θ^{th} row by the same; these multiplications will not affect the equality to zero of the determinant so modified, but the effect of the combined multiplications will be to change the element in the i^{th} row and j^{th} column, viz. (i, j), into $\frac{(I, J)}{(i, j)}(i, j)$, i. e. into (I, J). Thus it is proved that we may pass from the first reading of the (i, j) determinant to the second; and this in its turn serves to prove that if six lines are in involution their polars in respect to any quadric must also be in involution.

The theory of involution may of course be extended to a system of $\frac{n(n+1)}{2}$ lines in n-dimensional space.

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Note on Determinants of Powers.

By O. H. Mitchell.

If $\alpha > \beta > \gamma > \delta$, then

$$\begin{vmatrix} a^\alpha & a^\beta & a^\gamma & a^\delta \\ b^\alpha & b^\beta & b^\gamma & b^\delta \\ c^\alpha & c^\beta & c^\gamma & c^\delta \\ d^\alpha & d^\beta & d^\gamma & d^\delta \end{vmatrix} \div \begin{vmatrix} a^3 & a^2 & a^1 & a^0 \\ b^3 & b^2 & b^1 & b^0 \\ c^3 & c^2 & c^1 & c^0 \\ d^3 & d^2 & d^1 & d^0 \end{vmatrix} = \begin{vmatrix} \alpha^3 & \alpha^2 & \alpha^1 & \alpha^0 \\ \beta^3 & \beta^2 & \beta^1 & \beta^0 \\ \gamma^3 & \gamma^2 & \gamma^1 & \gamma^0 \\ \delta^3 & \delta^2 & \delta^1 & \delta^0 \end{vmatrix} \div \begin{vmatrix} 3^3 & 3^2 & 3^1 & 3^0 \\ 2^3 & 2^2 & 2^1 & 2^0 \\ 1^3 & 1^2 & 1^1 & 1^0 \\ 0^3 & 0^2 & 0^1 & 0^0 \end{vmatrix}$$

terms, *all positive* ($0^0 = 1$). In briefer notation, representing the first two determinants by their principal diagonals, and writing $\zeta_3^{\frac{1}{2}}(x, y, z, t)$ for $(x-y)(x-z)(x-t)(y-z)(y-t)(z-t)$,

$$\frac{(a^\alpha b^\beta c^\gamma d^\delta)}{(a^3 b^2 c^1 d^0)} = \frac{\zeta_3^{\frac{1}{2}}(\alpha, \beta, \gamma, \delta)}{\zeta_3^{\frac{1}{2}}(3, 2, 1, 0)} \text{ terms, } \textit{all positive};$$

and the like is true for determinants of any order. Calling the left-hand member Q_4, the subscript denoting the order of the determinants, Q_4 may be expressed as a linear function with positive coefficients of similar quotients, Q_3; and by successive applications of this formula Q_4 is expressible as $\Sigma a^p b^q c^r d^s$, where p, q, r, s are functions of the two sets of exponents, $\alpha, \beta, \gamma, \delta$ and $3, 2, 1, 0$, and of $(4-1)!$ variables whose limits in the summation are certain functions of $\alpha, \beta, \gamma, \delta$. And the like is true for determinants of any order.

For a proof of the preceding, consider the expression for Q_4 as given by Prof. Cayley, Salmon's Higher Algebra, p. 292, viz:

$$\frac{(a^\alpha b^\beta c^\gamma d^\delta)}{(a^3 b^2 c^1 d^0)} = \begin{vmatrix} H_{\alpha-3} & H_{\beta-3} & H_{\gamma-3} & H_{\delta-3} \\ H_{\alpha-2} & H_{\beta-2} & H_{\gamma-2} & H_{\delta-2} \\ H_{\alpha-1} & H_{\beta-1} & H_{\gamma-1} & H_{\delta-1} \\ H_\alpha & H_\beta & H_\gamma & H_\delta \end{vmatrix},$$

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... H_n ... of a ... to ... and ... of ... $\alpha+\beta+\gamma-3$ ... of the ... α, β, γ ... H_n ... H_{n-1}, H_{n-2} ... H_{n-1}, H_{n-2}, $H_{n-3}

By successive applications of this formula we get,

$$\frac{(a^{\alpha_1}b^{\alpha_2}c^{\alpha_3}d^{\alpha_4})}{(a^1b^2c^1d^0)} = \sum_{x_1=\alpha_2-\alpha_4}^{x_1=\alpha_1-\alpha_4-1} \sum_{x_2=\alpha_3-\alpha_4}^{x_2=\alpha_2-\alpha_4-1} \sum_{x_3=0}^{x_3=\alpha_3-\alpha_4-1} \sum_{y_1=x_3-x_2}^{y_1=x_1-x_2-1} \sum_{y_2=0}^{y_2=x_2-x_3-1} \sum_{z_1=0}^{z_1=y_1-y_2-1} a^p b^q c^r d^s,$$

where
$$p = (\alpha_1 + \alpha_2 + \alpha_3 + \alpha_4 - 3) - 4\alpha_4 - (x_1 + x_2 + x_3) + (\alpha_4),$$
$$q = (x_1 + x_2 + x_3 - 2) - 3x_3 - (y_1 + y_2) + (\alpha_4 + x_3),$$
$$r = (y_1 + y_2 - 1) - 2y_2 - (z_1) + (\alpha_4 + x_3 + y_2),$$
$$s = (z_1 - 0) - z_1 - (0) + (\alpha_4 + x_3 + y_2 + z_1).$$

The notation is slightly changed, and the values of p, q, r, s are written in a somewhat redundant form, in order to show more clearly the law for determinants of higher orders.

Since the number of terms in the H_n of n letters is expressed by the binomial coefficient C_{n-1}^{n+n-1}, the number of terms in the summation above (*i. e.* the sum of the coefficients, all of which are positive) is equal to the determinant

$$(C_3^{\alpha_3} C_2^{\alpha_2+1} C_3^{\alpha_3+2} C_2^{\alpha_4+3}), = (C_1^{\alpha_1} C_1^{\alpha_2} C_1^{\alpha_3} C_0^{\alpha_4}), = \frac{\zeta^1(\alpha_1, \alpha_2, \alpha_3, \alpha_4)}{\zeta^1(3, 2, 1, 0)},$$

obtained from the H-determinant. As an example,

$$\frac{(a^5b^2c^0)}{(a^1b^2c^0)} = \Sigma a^5b^1 + \Sigma a^5bc + \Sigma a^4b^3 + 2\Sigma a^4b^2c + 2\Sigma a^3b^3c + 3\Sigma a^3b^2c^2,$$

which has $42, = \frac{\zeta^1(7, 3, 0)}{\zeta^1(2, 1, 0)}$, terms.

If a_1, a_2, etc., be the n roots of $x^n - P_1x^{n-1} + P_2x^{n-2} - \text{etc.} = 0$, by substituting the roots and solving for P_r we get

$$P_r = \frac{(a_1^n a_2^{n-1} \ldots a_r^{n-r+1} a_{r-1}^{n-r-1} \ldots a_{n-1}^1 a_n^0)}{(a_1^{n-1} a_2^{n-2} \ldots a_r^{n-r} a_{r-1}^{n-r-1} \ldots a_{n-1}^1 a_n^0)}.$$

Thus $\frac{(a^1b^2c^3d^0)}{(a^0b^1c^1d^1)} = \Sigma abc$, and since the number of terms in Σabc is C_3^4, we get the following expression for the value of the binomial coefficient, C_3^4, viz:

$$C_3^4 = \frac{\zeta^1(4, 3, 2, 0)}{\zeta^1(3, 2, 1, 0)}.$$

And, in general, we have

$$C_r^n = \frac{\zeta^1(n, n-1, \ldots n-r+1, n-r-1, \ldots 2, 1, 0)}{\zeta^1(n-1, n-2, \ldots n-r, n-r-1, \ldots 2, 1, 0)},$$

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[illegible]

$$\begin{vmatrix} H_n(a,b,c) & H_{n-1}(a,b,c) & H_{n-2}(a,b,c) \\ H_{n-1}(b,c) & H_{n-2}(b,c) & H_{n-3}(b,c) \\ H_{n-2}(c) & H_{n-3}(c) & H_{n-4}(c) \end{vmatrix}$$

and since $bH_{n-1}(b,c) + H_n(c) = H_n(b,c)$, and $aH_{n-1}(a,b,c) + H_n(b,c) = H_n(a,b,c)$, etc., the determinant on the right is at once reduced by combination of rows to the similar determinant already considered, in which each row involves every letter, and which is obtained in the text-books, as far as I have observed, only by an indirect process. The method obviously applies to determinants of any order. The following evident identity is used in the reduction:

$$H_n(a,c,d,e,\ldots z) - H_n(b,c,d,e,\ldots z) = (a-b)\,H_{n-1}(a,b,c,\ldots z).$$

The above process of reduction shows that the value of the H-determinant is the same for every distribution of the letters among the rows, subject to the conditions (1) that the letters of every row are contained in each of the preceding rows, and (2) that no row contains *less* than $\omega - r + 1$ letters, where ω is the order of the determinant, and r is the number of the row, counting from the top.

BALTIMORE, 30 *May*, 1882.

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Determination of the Finite Quaternion Groups.

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If we apply to a set of quaternions the definition of a group as given in the Theory of Substitutions, then a *quaternion group* of the m^{th} order means a set of m quaternions (scalar unity always included) whose products and powers are also quaternions of the same set or group. The object of the present paper is to determine all the possible finite quaternion groups.

These groups, or rather their analogues in the ordinary Theory of Functions, have usually been interpreted geometrically as the linear transformations of the plane of complex variables in itself—*automorphic transformations*. The formulae for these linear transformations were first given by Professor Gordan in his paper "Ueber endliche Gruppen linearer Transformationen einer Veränderlichen."* The quaternion formulae, although they have their exact correspondents in Gordan's algebraic formulae, have, when interpreted geometrically, a more general character, in that they represent certain automorphic linear transformations of a three-dimensional infinite homoloidal space, or what is the same thing, of a three-fold extended sphere. The determination of these formulae might be made to depend upon Gordan's solution, but the following is a shorter and simpler solution than that of Gordan, and includes it as a special case.

Some General Formulae.

Let q, r represent two quaternions belonging to a finite group. In order that the group may be finite, the tensors of q, r, etc., must be unity, so that q and r may be written in the form

$$q = \cos\phi + \lambda \sin\phi,$$
$$r = \cos\psi + \mu \sin\psi,$$

* *Math. Ann.* Bd. XII, pp. 23–46. Compare also Cayley "On the finite Groups of linear Transformations of a Variable," *Math. Ann.* Bd. XVI, pp. 260–63, 439–40. The proof concerning the number and character of the possible groups was given by Prof. Klein, *Math. Ann.* Bd. IX, pp. 183–208: "Ueber binäre Formen mit linearen Transformationen in sich selbst."

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ϕ, ψ being the arguments, λ, μ the axes of q, r respectively. According to definition qr is also a member of the group, and if we write

$$(\iota.) \qquad qr = \cos\chi + \sigma \sin\chi,$$

χ represents a new argument and σ a new axis of the group, and they are determined by the relations

$$(\iota.) \qquad \sigma \sin\chi = \lambda \sin\phi \cos\psi + \mu \sin\psi \cos\phi - V\lambda\mu \sin\phi \sin\psi,$$

$$(\iota\iota.) \qquad \cos\chi = \cos\phi \cos\psi - S\lambda\mu \sin\phi \sin\psi$$

$$= \cos^2\frac{f}{2}\cos(\phi-\psi) - \sin^2\frac{f}{2}\cos(\phi+\psi),$$

where f is the angle formed by λ with μ.

In particular, we have the well-known formulæ

$$q^2 = \cos 2\phi + \lambda \sin 2\phi$$

$$\cdots\cdots\cdots\cdots$$

$$(\iota\nu) \qquad q^n = \cos n\phi + \lambda \sin n\phi.$$

In order that q may belong to a finite group, it is further necessary that some finite power of q should reproduce the *identity*—i.e. unity—so that, e.g., $q^m = 1$; ϕ is then a rational multiple of π; m is called the period of q.

I. In the following discussion it is important to remember that *when two quaternions of the same group have the same axis, they can always be written as powers of one and the same quaternion.*

Limits of the Periods.

Amongst the quaternions of the group there is one set—or one quaternion at least—whose argument is the smallest which the group contains. Let q be such a quaternion, and moreover such that its axis λ forms with some other axis μ of the group the smallest angle (the case $\lambda = \pm\mu$ excluded) which the axis of *any* quaternion of the group with the smallest argument can form with *any* other axis of the group. Under this hypothesis we have, if r be the quaternion whose axis is μ,

$$TV.\mu UVrqr \geqq TV\lambda\mu.$$

From the product rqr is deduced easily

$$V.\mu Vrqr = TVq \,.\, V\mu\lambda,$$

$$(\nu) \qquad V.\mu UVrqr = \frac{TVq}{TVrqr} \,.\, V\mu\lambda.$$

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In order that the condition $TV.\mu UVrq\,r \geqq TV\lambda\mu$ may be fulfilled, we must therefore have

(vi) $$V^2q \geqq V^2rq\,r, \text{ or } S^2q \leqq S^2q\,r^2,$$

i. e. $$\cos^2\phi \leqq \cos^2\theta,$$

where θ is the argument of rqr; ϕ, however, is by hypothesis the smallest argument which the group can possess, so that the only possible supposition is

$$\cos^2\phi = \cos^2\theta, \text{ or } S.q\,r^2 = \pm Sq.$$

Remembering that $S^2r - V^2r = 1$ (since $Tr = 1$) and that $r = Sr + Vr$, we have, if the sign before the second member be plus,

(vii) $$Sr \,.\, Sqr = 0,$$

but if minus,

$$S.rqr\,Vr = 0.$$

The latter of these conditions, however, would give

$$S\lambda\mu \,.\, \tan\phi = \tan\psi;$$

now as ψ by hypothesis cannot be smaller than ϕ, we should have

$$S\lambda\mu = \pm 1, \; i.e. \; \lambda = \pm\mu,$$

and r would be a power of q, a case we evidently do not need to consider. We have remaining therefore only the former condition $Sr \,.\, Sqr = 0$, which compels us to write either

$$Sr = 0, \text{ or } Sqr = 0.$$

The case $Sr = 0$ affords a possible solution, and determines for r the period 4.

But perhaps $Sqr = 0$ is also a solution. On the supposition that it is, write qr in the form

$$qr = q^{\frac{1}{2}} q^{\frac{1}{2}} r q^{\frac{1}{2}} q^{-\frac{1}{2}}.$$

This equation shows that the axes of qr and $q^{\frac{1}{2}} rq^{\frac{1}{2}}$ make equal angles with the axis of q. This angle cannot be smaller than the angle between λ and μ, and we have, if we rewrite the condition (vi) for this case,

(vi)′ $$S^2qr \geqq S^2r,$$

so that the condition $Sqr = 0$ demands also that $Sr = 0$; that is, the two conditions in question are equivalent, and r has in any case the period 4. We have therefore the following result:

II. *If q and r belong to a finite quaternion group, and if the argument of q is the smallest which the group contains, and if the angle between the axes of q and r is the smallest one existing between the axis of a quaternion with the smallest argument*

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and any other axis of the group (the angle zero or 2Θ excepted), then $Sr = 0$ and r has of necessity the period 4.

One quaternion belonging to the group is

$$q' = rqr^{-1} = \cos\phi + \lambda' \sin\phi,$$

where $\lambda' = \mu\lambda\mu^{-1}$. If now we form the product $qq'q$—which must also be a quaternion of the group—we shall find, by the same process as that by which (v) was found, that

$$(v)' \qquad V.\lambda U V_{qq'q} = \frac{\sin\varphi}{TV_{qq'q}} \cdot V\lambda\lambda',$$

and since ϕ is the smallest argument of the group,

$$\sin\phi \leqq TV_{qq'q},$$

from which and the preceding equation it follows, that

$$(viii) \qquad TV.\lambda U V_{qq'q} \leqq TV\lambda\lambda'.$$

This last inequality shows that the axis of $qq'q$, if it do not coincide with λ or λ', must lie between them and therefore coincide with μ, for μ is the only axis lying between these limits. We have therefore three possibilities:

$$qq'q = q^x, \text{ or } qq'q = q^y, \text{ or } qq'q = \mu^z,$$

where x, y, z are integers. The case $qq'q = q^x$, if we develop the equation $qq' = q^x q^{-1}$ and operate with $V.\lambda$ on the result, gives

$$0 = V.\lambda\lambda' \operatorname{ctn}\phi + V.\lambda V\lambda\lambda',$$

$$(ix) \qquad 0 = V.\lambda\lambda' \operatorname{ctn}\phi - \lambda' - \lambda S\lambda\lambda';$$

and finally, by means of the operation $S.\lambda'$,

$$S^2\lambda\lambda' = 1,$$

which means simply—according to (I)—that q' is a power of q. The second case $qq'q = q^y$ and the case $qq'q = \pm\mu^z = \pm 1$, give a similar result, since q' becomes respectively $q' = q^{y-x}$ and $q' = \pm q^{-x}$. We therefore conclude,

III. *That the quaternion $quqv^{-1}q$, if it belong to a finite group, is either a power of q, or is equal to $\pm\mu$; provided μ, as compared with all the other axes of the group, forms with the axis of q the minimum angle.*

Groups which have a period greater than 10.

In order that the equation $qq'q = q^r$ (or $q' = q^{r-2}$) may be satisfied, we must have $\mu\lambda\mu^{-1} = \pm\lambda$, which demands further, that either

$$(x) \qquad V\lambda\mu = 0, \text{ or}$$

$$(xi) \qquad S\lambda\mu = 0,$$

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that is, μ is either parallel or perpendicular to λ. If however $qq'q = \pm\mu$ should be satisfied, then

$$Sqq'q = \cos\phi\cos 2\phi + S\lambda\lambda'\sin\phi\sin 2\phi = 0,$$

$$S\lambda\lambda' = -\operatorname{ctn}\phi\operatorname{ctn} 2\phi. \tag{xii}$$

The smallest value which ϕ can here assume is $\frac{\partial}{6}$, and corresponding to this value we have

$$S\lambda\lambda' = -1, \quad \lambda' = \lambda = \mu = q^3;$$

that is, r is a power of q, a case we do not consider. The condition $qq'q = \pm\mu$, therefore, is only possible when ϕ is greater than $\frac{\partial}{6}$, *i. e.* when q has a period less than 12; and since it will be shown in the sequel (p. 353, VI) that the largest period of a finite group having more than a single axis must be an even period, it follows that the condition in question can exist only when the period of q does not exceed 10. We have, therefore, if the period of q be greater than 10, the single condition (xi), the condition (x) being irrelevant. Since of all the axes of the group μ has the greatest inclination to the axis of q, it follows from the results just obtained, that

IV. *If q has a period greater than* 10, *all the axes of the group, except that of q itself, lie in the plane—passing through the origin—to which the axis of q is perpendicular.*

It will next be shown, that

V. *Of a group containing a period greater than* 10, *all the quaternions which are not powers of q have either the period* 4 *or* 2.

If there be a quaternion s of the group, whose period is different from 4 or 2 and which is not a power of q, then there must be several such—with different axes, but with the same argument—which can be formed by means of the transformations qsq^{-1}, q^2sq^{-2}, . . . Let us suppose, therefore, that there are two such quaternions s, s' with the argument χ and the axes ν, ν'. Then by IV, either Vss' coincides with λ, or else it lies in the same plane with Vs and Vs'; that is, we must have either

$$S.\nu Vss' = S.\nu' Vss' = 0,$$

or

$$S.\nu\nu' Vss' = 0.$$

These two equations are equivalent respectively to

$$(S\nu\nu' - 1).\sin 2\chi = 0$$

and

$$V^2\nu\nu'.\sin^2\chi = 0.$$

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Either equation would be satisfied by $S.\nu\nu' = 1$, or what is the same thing, by $V\nu\nu' = 0$, in which case, however, ν and ν' would, contrary to hypothesis, coincide; hence χ must be so chosen as to make either $\sin 2\chi$ or $\sin \chi$ vanish, that is to say, χ must be an integral multiple either of $\frac{\pi}{2}$, or of $\frac{\pi}{4}$.—*Q.E.D.*

Cyclotomic (Kreistheilungs) Groups. If the condition $qq'q = q'$, i.e. $V\lambda\mu = 0$, be fulfilled, all the axes of the group coincide with λ.

The group contains then only powers of a single quaternion q. If q be written in the form

$$q = \cos\frac{2\vartheta}{m} + \lambda\sin\frac{2\vartheta}{m},$$

we may assume as the generator of the group any power of q of the form q^a, where a is prime to m; the powers of q^a form a cyclotomic group of the m^{th} order. Since there are $\phi(m)$ numbers prime to m, there are $\phi(m)$ such cyclotomic groups composed of powers of q. Regarded as a whole, such groups are repetitions of each other written in different order.

If, besides the powers of q, there exist, as belonging to the group, only quaternions of the period 2, such quaternions are evidently all identical with each other and equal to -1. If this be combined with all the quaternions of a cyclotomic group of even order, say m, the resulting group will be a cyclotomic group of order $2m$, composed of the powers of $(-q)$. If, on the other hand, a cyclotomic group of even order be combined with -1, the result will be the same cyclotomic group again.

The Double-Pyramid Groups. If besides the m powers of q, m being even, there exists in the group a quaternion having the period 4, which we may represent by the vector μ—and μ is in this case also perpendicular to λ—then, by combining μ with all the powers of q, we can form m other quaternions

$$\mu q,\ \mu q^2,\ \ldots\ \mu q^m,$$

(or what is the same thing $q\mu,\ q^2\mu,\ \ldots\ q^m\mu$, since $\mu q^s = q^{-s}\mu$) which together with the m powers of q compose a group of the order $2m$. If, however, m be odd, then besides the $2m$ quaternions just mentioned, the group will contain $2m$ other quaternions

$$\mu^2 q,\ \mu^2 q^2,\ \ldots\ \mu^2 q^m \quad [\mu^2 = -1]$$
$$\mu^3 q,\ \mu^3 q^2,\ \ldots\ \mu^3 q^m \quad [\mu^3 = -\mu],$$

and the group will therefore be of the order $4m$. Hence the order of every quaternion group of this type is a multiple of 4.

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Suppose $4m$ to be the order of a double-pyramid group. Then q has the period $2m$, and we have just seen that there are $\phi(2m)$ different powers of q, represented by q^α (where α is prime to m) any one of which will generate the cyclotomic group of the $2m^{\text{th}}$ order. We can use any one of these powers q^α as one of the generators of the double-pyramid group of the $2m^{\text{th}}$ order, μ being the other generator, and can thus obtain this group also in $\phi(2m)$ different forms.

Groups containing no Period greater than 10.

The Period 10. If q has a period not exceeding 10, we have then, for the determination of the angle between λ and μ, the condition (xii), p. 349, viz:

(xii) $$S.(\lambda\mu)^3 = S\lambda\lambda' = -\operatorname{etn}\phi \operatorname{etn} 2\phi.$$

For the period 10, therefore, we have

$$S\lambda\lambda' = -\cos 2f = -\operatorname{etn}\frac{\Theta}{5}\cdot\operatorname{etn}\frac{2\Theta}{5},$$

if $2f$ denote the angle which λ makes with λ', *i. e.* if f be the angle between λ and μ. Hence

$$\cos 2f = \frac{1}{\sqrt{5}},\ \cos f = \sqrt{\frac{e}{\sqrt{5}}} = -S\lambda\mu$$

where $e = \frac{1+\sqrt{5}}{2}$. If we write $\mu = i$ and make the plane of (λ, μ) that of (i, k), we shall find the values of λ and q to be

$$\lambda = i\cos f + k\sin f = \frac{i - e'k}{\sqrt{1+e'^2}},$$

$$q = \cos\frac{\Theta}{5} + \lambda\sin\frac{\Theta}{5} = \frac{e + i - e'k}{2},$$

where $e' = \frac{1-\sqrt{5}}{2}$. By combining q and i and their powers and products in all possible ways, we shall generate a closed group consisting of 120 different quaternions:—the *Double-Ikosahedron Group*. q and i are called the generators of the group. (The quaternions of this and the following groups are written out in full in the accompanying tables $I_m - Q_{120}$, pp. 354, 355.)

Having chosen $\mu = i$, we might then have written, instead of

$$\lambda = i\cos f + k\sin f,$$

this value:

$$\lambda = i\cos f + j\sin f.$$

The latter assumption would evidently—on account of the symmetry of the i, j, k, in their relations to each other—result in a group similar to the

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one determined by the former value of λ. It will be found that the two groups differ only by an interchange of e and e', and it is also easy to show that the former group becomes the latter by applying to it the transformation $(1-k)(\ )(1-k)^{-1}$; that is, by writing, in the former group, for each quaternion q the quaternion $(1-k).q.(1-k)^{-1}$. Two such groups are called similar and isomorphic*.

The Period 8. If q has the period 8, then $\phi = \frac{\Theta}{4}$ and

$$S\lambda\lambda' = -\cos 2f = -\operatorname{ctn}\frac{\Theta}{4}\operatorname{ctn}\frac{\Theta}{2} = 0,$$

$$f = \frac{\Theta}{4}.$$

Writing $\lambda = i$, we have

$$q = \frac{1+i}{\sqrt{2}},$$

and since μ forms with λ an angle of 45°, we may assume

$$\mu = \frac{i+j}{\sqrt{2}}.$$

q and μ will then be the generators of a closed group of 48 quaternions:—the *Double-Oktahedron Group*. The choice $\mu = \frac{i+k}{\sqrt{2}}$ could evidently equally well have been made; it turns out however that q and $\frac{i+k}{\sqrt{2}}$ generate the same group as q and $\frac{i+j}{\sqrt{2}}$.

The Period 6. If 6 be the period of q, then $\phi = \frac{\Theta}{3}$ and

$$S\lambda\lambda' = -\cos 2f = -\operatorname{ctn}\frac{\Theta}{3}\operatorname{ctn}\frac{2\Theta}{3} = \frac{1}{3},$$

$$\cos f = \frac{1}{\sqrt{3}}.$$

Here, if we write $\mu = i$ and determine the plane (λ, μ) in such a way that it bisects the angle between j and k, we shall have for the values of λ and q

$$\lambda = \frac{j+k}{\sqrt{2}}\sin f + i\cos f = \frac{i+j+k}{\sqrt{3}},$$

$$q = \frac{1+i+j+k}{2}.$$

* C. Jordan, Traité des substitutions et des equations algebriques, pp. 23, 56.

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q and i are the generators of a group of the 24th order:—the *Double-Tetrahedron Group.*

The Period 4. If q have the period 4, then $q = \lambda$. If the condition (xii) be applied to this case, we find $Sq\lambda/q = 0 = S\lambda\lambda'$, $f = \frac{\Theta}{4}$, and thus obtain the same value of f which gave rise to the double-oktahedron group; and we should in fact obtain this same group for the above value of f in the present case. This results from the fact that the product $\lambda\mu$ would be a quaternion having 8 for its period. We may therefore throw aside the condition (xii) and applying (xi)—*i. e.* $S\lambda\mu = 0$—write

$$\lambda = i, \quad \mu = j,$$

which two quaternions are the generators of the well-known group of the 8th order, viz. ± 1, $\pm i$, $\pm j$, $\pm k$. This is a special example of the double-pyramid type.

The Periods 11, 9, 7, 5, 3. In order to prove that the above enumeration of the finite quaternion groups is exhaustive, it will only be necessary to show,

VI. *That the greatest period contained in any finite quaternion group, which is not a cyclotomic group, is even.*

The smallest argument which can belong to an odd period m is $\frac{2\Theta}{m}$. If such an argument however belong to a finite group which possesses more than a single axis, it cannot be the smallest argument in the group; for if q be the quaternion whose argument is $\frac{2\Theta}{m}$, m being odd, and if μ be as before the axis most inclined to that of q, then $qm^{s}q^{\frac{m-1}{2}} = -q^{\frac{m+1}{2}}$ belongs to the group, and since

$$\begin{aligned} -q^{\frac{m+1}{2}} &= -\cos\frac{m+1}{2}\Theta - \lambda\sin\frac{m+1}{2}\Theta \\ &= \cos\left(2m\Theta + \frac{\Theta}{m}\right) + \lambda\sin\left(2m\Theta + \frac{\Theta}{m}\right) \\ &= \cos\frac{\Theta}{m} + \lambda\sin\frac{\Theta}{m}, \end{aligned}$$

therefore the group contains the argument $\frac{\Theta}{m}$, which is half of $\frac{2\Theta}{m}$, and thus the proposition is proved. With this demonstration ends the possibility of forming any other class of finite quaternion groups than those above enumerated.

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Tables of the Five Different Types of Groups.

The explicit formulae which constitute the five different types of groups are contained in the following tables. $N =$ order of the group.

I_m.

The Cyclotomic Groups.

These have the form

$$q^a,\ q^{3a},\ \ldots .\ q^{ma};\quad N = m,\ a \text{ prime to } m;$$

where q is any quaternion having the period m.

J_{4n}.

1. *The Double-Pyramid Groups.*

These have the form

$$q^a,\ q^{3a},\ \ldots .\ q^{2na},$$
$$\mu q^a,\ \mu q^{3a},\ \ldots .\ \mu q^{2na};\quad N = 4n,\ a \text{ prime to } 2n;$$

where q is any quaternion having the period $2n$, and where μ is a vector lying in the plane perpendicular to the axis of q. $[S\lambda\mu = 0.]$

2. Q_8: *The i-j-k Group*, viz:

$$\pm 1,\ \pm i,\ \pm j,\ \pm k.$$

This is a special case of J_{4n}.

Q_{24}.

The Double-Tetrahedron Group.

$$i^\varepsilon,\quad j^\eta,\quad k^\zeta,$$
$$\left(\frac{1+i+j+k}{2}\right)^\nu,\quad \left(\frac{1-i-j+k}{2}\right)^\nu,\quad \left(\frac{1+i-j-k}{2}\right)^\nu,\quad \left(\frac{1-i+j-k}{2}\right)^\nu;$$
$$\varepsilon = 1,\ 2,\ 3,\ 4;\quad \eta = 1,\ 2,\ 3,\ 4,\ 5,\ 6;\quad N = 24.$$

Q_{48}.

The Double-Oktahedron Group.

$$\left(\frac{1+i}{\sqrt{2}}\right)^\varepsilon,\qquad \left(\frac{1+j}{\sqrt{2}}\right)^\eta,\qquad \left(\frac{1+k}{\sqrt{2}}\right)^\zeta;$$
$$\left(\frac{1+i+j+k}{2}\right)^\nu,\quad \left(\frac{1-i-j+k}{2}\right)^\nu,\quad \left(\frac{1+i-j-k}{2}\right)^\nu,\quad \left(\frac{1-i+j-k}{2}\right)^\nu;$$
$$\left(\frac{j+k}{\sqrt{2}}\right)^\xi,\qquad \left(\frac{k+i}{\sqrt{2}}\right)^\xi,\qquad \left(\frac{i+j}{\sqrt{2}}\right)^\xi,$$
$$\left(\frac{j-k}{\sqrt{2}}\right)^\xi,\qquad \left(\frac{k-i}{\sqrt{2}}\right)^\xi,\qquad \left(\frac{i-j}{\sqrt{2}}\right)^\xi;$$
$$\varepsilon = 1,\ \ldots .\ 8;\quad \eta = 1,\ \ldots .\ 6;\quad \zeta = 1,\ \ldots .\ 4;\quad N = 48.$$

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Q_{120}.

1. *The Double-Ikosahedron Group.*

$$\begin{array}{ccc} i^\varepsilon & j^\varepsilon & k^\varepsilon \\ \left(\frac{i+\epsilon' j+\epsilon k}{2}\right)^\varepsilon, & \left(\frac{j+\epsilon' k+\epsilon i}{2}\right)^\varepsilon, & \left(\frac{k+\epsilon' i+\epsilon j}{2}\right)^\varepsilon, \\ \left(\frac{i-\epsilon' j+\epsilon k}{2}\right)^\varepsilon, & \left(\frac{j-\epsilon' k-\epsilon i}{2}\right)^\varepsilon, & \left(\frac{k+\epsilon' i-\epsilon j}{2}\right)^\varepsilon, \\ \left(\frac{i+\epsilon' j-\epsilon k}{2}\right)^\varepsilon, & \left(\frac{j-\epsilon' k+\epsilon i}{2}\right)^\varepsilon, & \left(\frac{k-\epsilon' i-\epsilon j}{2}\right)^\varepsilon, \\ \left(\frac{i-\epsilon' j-\epsilon k}{2}\right)^\varepsilon, & \left(\frac{j+\epsilon' k-\epsilon i}{2}\right)^\varepsilon, & \left(\frac{k-\epsilon' i+\epsilon j}{2}\right)^\varepsilon; \end{array}$$

$$\left(\frac{1+i+j+k}{2}\right)^\eta, \quad \left(\frac{1-i-j+k}{2}\right)^\eta, \quad \left(\frac{1+i-j-k}{2}\right)^\eta, \quad \left(\frac{1-i+j-k}{2}\right)^\eta,$$

$$\begin{array}{ccc} \left(\frac{1+\epsilon j+\epsilon' k}{2}\right)^\eta, & \left(\frac{1+\epsilon k+\epsilon' i}{2}\right)^\eta, & \left(\frac{1+\epsilon i+\epsilon' j}{2}\right)^\eta, \\ \left(\frac{1+\epsilon j-\epsilon' k}{2}\right)^\eta, & \left(\frac{1+\epsilon k-\epsilon' i}{2}\right)^\eta, & \left(\frac{1+\epsilon i-\epsilon' j}{2}\right)^\eta; \end{array}$$

$$\begin{array}{ccc} \left(\frac{\epsilon+\epsilon' j+k}{2}\right)^\zeta, & \left(\frac{\epsilon+\epsilon' k+i}{2}\right)^\zeta, & \left(\frac{\epsilon+\epsilon' i+j}{2}\right)^\zeta, \\ \left(\frac{\epsilon+\epsilon' j-k}{2}\right)^\zeta, & \left(\frac{\epsilon+\epsilon' k-i}{2}\right)^\zeta, & \left(\frac{\epsilon+\epsilon' i-j}{2}\right)^\zeta; \end{array}$$

$$\varepsilon = 1, \ldots . 4; \quad \eta = 1, \ldots . 6; \quad \zeta = 1, \ldots . 10; \quad N = 120.$$

$$\epsilon = \frac{1+\sqrt{5}}{2}, \quad \epsilon' = \frac{1-\sqrt{5}}{2}.$$

2. Q_{120}: A second Double-Ikosahedron Group differing from the above by the interchange of ϵ with ϵ'.

The groups Q_8 and Q_{24} are contained in Q_{48}, and Q_8 in Q_{24}, as permutable sub-groups.* Also a double-pyramid group of the $4m^{\text{th}}$ order contains a cyclotomic group of the $2m^{\text{th}}$ order as a *permutable* (ausgezeichnet) sub-group. The group Q_{120} contains no *permutable* sub-group except the group ± 1 of the 2^{d} order.

The vectors of the quaternions of these various groups represent geometrically the axes of symmetry of the corresponding regular polyhedra; that is, they are the diameters of the circumscribed sphere, which pass either through summits, or middle points of faces, or middle points of edges.

* C. Jordan, "Traité des substitutions," pp. 1–50; and W. Dyck, "Gruppe und Irrationalität regulärer Riemann'schen Flächen," *Math. Ann.* Bd. XVII, p. 481.

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The Groups of Movements of the Regular Polyhedra in three-dimensional Space.

It is well known that any displacement of a sphere about its centre as a fixed point can be replaced by a simple rotation about a determinate axis, and that such a rotation is represented by the operator $q(\ )q^{-1}$, q being a quaternion whose axis is the axis of rotation and the double of whose angle is the amount of rotation. From the foregoing discussion, therefore, it follows immediately that all the finite groups of automorphic transformations of the sphere are represented by the various groups of operations of the form $q(\ )q^{-1}$, when, for a given group, q assumes all the values of the different quaternions in some one of the above enumerated quaternion groups. The linear transformations of Gordan are therefore represented in the following scheme.

$I_m(\ )I_m^{-1}$. If q assume all the values of the quaternions of a cyclotomic group of the m^{th} or $2m^{th}$ order, m being odd, then the operators of $q(\ )q^{-1}$, $q^2(\ )q^{-2}$, ... $q^m(\ )q^{-m}$ represent the m movements, or rotations about the axis of q, which transport any vertex of a polygon of m sides—whose plane is perpendicular to the axis of q—into all the other vertices of the polygon successively. These rotations I call the automorphic or self-congruent movements of the polygon.*

$J_{4n}(\ )J_{4n}^{-1}$. If q assume successively the values of the quaternions of a double-pyramid group of the order $4n$, the resulting rotations $q(\ )q^{-1}$ will represent all the self-congruent movements (*Bewegungen in sich*) of a double pyramid having in all $4n$ faces.

$Q_{24}(\ )Q_{24}^{-1}$. If q assume successively the values of the quaternions of the group Q_{24}, then the operators $q(\ )q^{-1}$ represent the 12 self-congruent movements of the tetrahedron, such that its four summits

$$\frac{i+j+k}{\sqrt{3}}, \quad \frac{-i-j+k}{\sqrt{3}}, \quad \frac{i-j-k}{\sqrt{3}}, \quad \frac{-i+j-k}{\sqrt{3}},$$

its four centres of faces

$$-\frac{i+j+k}{\sqrt{3}}, \quad -\frac{-i-j+k}{\sqrt{3}}, \quad -\frac{i-j-k}{\sqrt{3}}, \quad -\frac{-i+j-k}{\sqrt{3}},$$

and its six middle points of edges

$$\pm i, \quad \pm j, \quad \pm k,$$

are separately permuted with each other.

* I call a figure self-congruent, when without undergoing any change as a whole, like parts—as points with points, lines with lines, etc.—are interchanged. Self-congruent movements or rotations are those which produce such an interchange of like elements; thus all the motions of a sphere about its centre as a fixed point are self-congruent movements.

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$Q_{48}(\,)\,Q_{48}^{-1}$. If the quaternions of the group Q_{48} be substituted for q in $q(\,)q^{-1}$, the resulting transformations will be the 24 self-congruent movements of the oktahedron. The summits of this oktahedron are

$$\pm i, \qquad \pm j, \qquad \pm k;$$

its centres of faces are

$$\pm\frac{i+j+k}{\sqrt{3}}, \quad \pm\frac{-i-j+k}{\sqrt{3}}, \quad \pm\frac{i-j-k}{\sqrt{3}}, \quad \pm\frac{-i+j-k}{\sqrt{3}};$$

and its middle points of edges are

$$\pm\frac{j\pm k}{\sqrt{2}}, \quad \pm\frac{k\pm i}{\sqrt{2}}, \quad \pm\frac{i\pm j}{\sqrt{2}};$$

and the movements in question permute these *like* elements with each other.

$Q_{120}(\,)\,Q_{120}^{-1}$. Finally, if in $q(\,)q^{-1}$, q be made to assume all the values in Q_{120}, the result will be the 60 self-congruent movements of the ikosahedron. We have here for summits

$$\pm\frac{\epsilon j\pm k}{\epsilon\sqrt{5}}, \quad \pm\frac{\epsilon k\pm i}{\epsilon\sqrt{5}}, \quad \pm\frac{\epsilon i\pm j}{\epsilon\sqrt{5}};$$

for centres of faces

$$\pm\frac{i+j+k}{\sqrt{3}}, \quad \pm\frac{-i-j+k}{\sqrt{3}}, \quad \pm\frac{i-j-k}{\sqrt{3}}, \quad \pm\frac{-i+j-k}{\sqrt{3}},$$
$$\pm\frac{\epsilon j\pm\epsilon k}{\sqrt{3}}, \quad \pm\frac{\epsilon k\pm\epsilon i}{\sqrt{3}}, \quad \pm\frac{\epsilon i\pm\epsilon j}{\sqrt{3}};$$

and for middle points of edges

$$\pm i, \qquad \pm j, \qquad \pm k,$$
$$\pm\frac{i\pm\epsilon j\pm\epsilon k}{2}, \quad \pm\frac{j\pm\epsilon k\pm\epsilon i}{2}, \quad \pm\frac{k\pm\epsilon i\pm\epsilon j}{2}.$$

The above scheme contains all the possible finite groups of automorphic linear transformations of the sphere, or what is the same thing, of the plane of complex variables.

SCHWARZBACH, SAXONY, *September*, 1881.

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The Counter-Pedal Surface of the Ellipsoid.

By Thomas Craig, *Johns Hopkins University.*

The particular surface investigated in the present paper is merely one of a class whose properties do not seem to have been studied: there is at least no reference to the surfaces in any works that I am acquainted with: further, Prof. Cayley expresses his belief that the subject is quite new. The definition of a counter-pedal surface is obtained from the definition of a pedal surface by a very slight change of the wording, thus: a pedal surface is the locus of the intersection of the tangent planes to a given surface with straight lines drawn from a given point parallel to the normal; the counter-pedal surface is the locus of the intersection of the normals to a given surface with planes drawn through a given point parallel to the tangent planes. We can have in like manner pedal curves and counter-pedal curves. Problems connected with counter-pedals, whether curves or surfaces, will in general be more difficult than those connected with pedals, as it would seem that in general the degree of the counter-pedal is higher than that of the pedal. Before taking up the analytical part of the work I must first express my great obligations to Prof. Cayley for the assistance he has given me in this connection, especially in finding the equation of the surface. I had found the equation of the surface, but in a complicated form and encumbered with a factor of the sixth degree, which I knew must exist but could not find. On presenting my difficulty to Prof. Cayley, he was good enough to work out for me the equation of the surface in another and simpler form. The investigation below to find the equation of the surface is, with some insignificant changes, entirely due to Prof. Cayley. I have also received assistance from him on many other minor points in working out the properties of this surface. I have not as yet done much on the general theory of counter-pedal surfaces and curves, but if one may judge anything from analogy in the case of the counter-pedals of the ellipse and ellipsoid, these new curves and surfaces seem to be more

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closely related to negative pedals than to the direct pedals. For example, the degree of the negative and counter-pedals of the ellipse is six; the degree of the negative and counter-pedals of the ellipsoid is ten; while the degree of the pedals is in each case four. In both of these cases the pole is supposed to be at the centre. If for the ellipse the pole is taken at the focus, the negative pedal is a curve of the fourth degree having the lines $x^2 + y^2 = 0$ for stationary tangents.

The counter-pedal surface of the ellipsoid, as considered in the following, is the locus of the intersections of central planes parallel to the tangent planes of the ellipsoid with the normals at the corresponding points of contact. The ellipsoid is given by the equation

$$\frac{\xi^2}{a^2} + \frac{\eta^2}{b^2} + \frac{\zeta^2}{c^2} = 1 .$$

The length of the central perpendicular upon the tangent plane to the ellipsoid at any point may be denoted by P; then

$$\frac{1}{P^2} = \frac{\xi^2}{a^4} + \frac{\eta^2}{b^4} + \frac{\zeta^2}{c^4} ;$$

further write

$$\alpha ,\ \beta ,\ \gamma = b^2 - c^2 ,\ c^2 - a^2 ,\ a^2 - b^2 .$$

Denote by x, y, z the coördinates of a point on the counter-pedal corresponding to a point ξ, η, ζ on the ellipsoid, then it is obvious that these are given by the equations

$$x = \xi\left(1 - \frac{P^2}{a^2}\right), \quad y = \eta\left(1 - \frac{P^2}{b^2}\right), \quad z = \zeta\left(1 - \frac{P^2}{c^2}\right).$$

In order to find the equation of the counter-pedal we have to eliminate ξ, η, ζ between these equations and

$$\frac{\xi^2}{a^2} + \frac{\eta^2}{b^2} + \frac{\zeta^2}{c^2} = 1 .$$

It is to be noticed that these equations give

$$x\xi + y\eta + z\zeta = x^2 + y^2 + z^2 ,$$

$$\frac{x\xi}{a^2} + \frac{y\eta}{b^2} + \frac{z\zeta}{c^2} = 0 ,$$

$$\frac{\xi}{a^2}(y\zeta - z\eta) + \frac{\eta}{b^2}(z\xi - x\zeta) + \frac{\zeta}{c^2}(x\eta - y\xi) = 0 .$$

The geometrical meaning of these equations is obvious; one should be able to eliminate between these and the equation of the ellipsoid and find the equa-

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tion of the surface. I was however not able to do it. The result was of the degree sixteen instead of ten, the proper degree: but I could not find the ninefold factor. Instead of $-t^2$ in the denominator we write merely t, then

$$x=\xi\left(\frac{a}{a+t}\right), \quad y=\eta\left(\frac{b}{b+t}\right), \quad z=\zeta\left(\frac{c}{c+t}\right);$$

from these by aid of

$$\frac{\xi^2}{a^2}+\frac{\eta^2}{b^2}+\frac{\zeta^2}{c^2}=1$$

we derive

$$\frac{x^2}{(a+t)^2}+\frac{y^2}{(b+t)^2}+\frac{z^2}{(c+t)^2}=1,$$

and

$$\frac{x^2}{(a+t)^2}+\frac{y^2}{(b+t)^2}+\frac{z^2}{(c+t)^2}=-\frac{1}{t}.$$

For greater convenience replace x^2, y^2, z^2, a^2, b^2, c^2 by x, y, z, a, b, c, then to find the required equation we have to eliminate t between

$$\frac{ax}{(a+t)^2}+\frac{by}{(b+t)^2}+\frac{cz}{(c+t)^2}=1$$

$$\frac{x}{(a+t)^2}+\frac{y}{(b+t)^2}+\frac{z}{(c+t)^2}=-\frac{1}{t}.$$

Multiply the second of these by t and add to the first; this gives

$$\frac{x}{a+t}+\frac{y}{b+t}+\frac{z}{c+t}=0,$$

which is to be combined with

$$\frac{ax}{(a+t)^2}+\frac{by}{(b+t)^2}+\frac{cz}{(c+t)^2}=1.$$

We have thus to eliminate t between a sextic and a quadratic equation. The method followed by Prof. Cayley to effect this elimination is as follows: Expanding the quadratic it is

$$(x+y+z)t^2+[(b+c)x+(c+a)y+(a+b)z]t+bcx+cay+abz=0.$$

Write this as

$$Pt^2+Qt+R=0.$$

Denote by t_1 and t_2 the roots of this quadratic, then we have

$$Pt^2+Qt+R=P(t-t_1)(t-t_2),$$

$$t_1+t_2=-\frac{Q}{P}, \quad t_1t_2=\frac{R}{P}.$$

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The minimum value of t is of course $-a$, and its maximum value $-c$. Make $t=-a$, then we have

$$a^3(x+y+z)-a(b+c)\,x+(c+a)\,y+(a+b)\,z)+bcx+cay+abz=P(a+t_1)(a+t_2)$$

and obviously

$$P(a+t_1)(a+t_2)=-\beta\gamma x$$
$$P(b+t_1)(b+t_2)=-\gamma\alpha y$$
$$P(c+t_1)(c+t_2)=-\alpha\beta z$$

The quantity $(t_1-t_2)^2$ will be needed; this is given by

$$(t_1-t_2)^2=\frac{Q^2-4PR}{P^2}.$$

Substituting for P, Q, R their values, this is

$$(t_1-t_2)^2=\frac{a^2x^2+\beta^2y^2+\gamma^2z^2-2\beta\gamma yz-2\alpha^2xy-2\gamma\alpha zx}{(x+y+z)^2}$$

or say

$$(t_1-t_2)^2=\frac{\Gamma}{P^2}.$$

The values of t_1 and t_2, substituted in the sextic equation, will lead to the expression required for the equation of the counter-pedal. The sextic expanded is

$$(b+t)^3(c+t)^3ax+(c+t)^3(a+t)^3by+(b+t)^3(a+t)^3cz-(a+t)^3(b+t)^3(c+t)^3=0.$$

Write this as

$$Aax+Bby+Ccz-D=0;$$

denote by the suffix 1 or 2 the result of substituting for t its values t_1 and t_2; multiplying together the two identical equations thus obtained we have

$$(A_1ax+B_1by+C_1cz-D_1)(A_2ax+B_2by+C_2cz-D_2)=0;$$

this expanded is

$$A_1A_2a^2x^2+B_1B_2b^2y^2+C_1C_2c^2z^2+D_1D_2$$
$$+(B_1C_2+B_2C_1)\,bcyz+(A_1C_2+A_2C_1)\,caxz+(A_1B_2+A_2B_1)\,abxy$$
$$-(A_1D_2+A_2D_1)\,ax-(B_1D_2+B_2D_1)\,by-(C_1D_2+C_2D_1)\,cz=0.$$

Using the above equations giving the values of x, y, z, the coefficients in this are readily found.

$$A_1A_2=(b+t_1)^3(b+t_2)^3(c+t_1)^3(c+t_2)^3=\frac{a^2\beta^2\gamma^2}{P^6}\cdot\alpha^3y^3z^3$$

$$D_1D_2=(a+t_1)^3(a+t_1)^3\ldots\ldots(c+t_2)^3=\frac{a^2\beta^2\gamma^2}{P^6}\cdot\alpha^3\beta^3\gamma^3x^3y^3z^3$$

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$$B_1C_1 + B_2C_2 = (c+t_1)^2(a+t_1)^2(a+t_2)^2(b+t_2)^2 + (c+t_2)^2(a+t_2)^2(a+t_1)^2(b+t_1)^2$$
$$= (a+t_1)^2(a+t_2)^2\left[(c+t_1)^2(b+t_2)^2 + (c+t_2)^2(b+t_1)^2\right]$$
$$= (a+t_1)^2(a+t_2)^2\left[a^2(t_1-t_2)^2 + 2\,\overline{b+t_1}\,.\,\overline{b+t_2}\,.\,\overline{c+t_1}\,.\,\overline{c+t_2}\right]$$
$$= \frac{\beta^2\gamma^2x^2}{P^2}\left[\frac{a^2\Gamma}{P^2} + 2\frac{a^2\beta\gamma yz}{P^2}\right]$$

$$A_1D_1 + A_2D_2 = (b+t_1)^2(c+t_1)^2(a+t_2)^2(b+t_2)^2(c+t_2)^2$$
$$+ (b+t_2)^2(c+t_2)^2(a+t_1)^2(b+t_1)^2(c+t_1)^2$$
$$= (b+t_1)^2(b+t_2)^2(c+t_1)^2(c+t_2)^2\left[(a+t_2)^2 + (a+t_1)^2\right] \cdot$$
$$= \frac{a^2\beta^2\gamma^2}{P^4}\cdot a^2y^2z^2\left[(t_1-t_2)^2 + 2(a+t_1)(a+t_2)\right]$$
$$= \frac{a^2\beta^2\gamma^2}{P^4}\cdot a^2y^2z^2\left[\frac{\Gamma}{P^2} - \frac{2\beta\gamma x}{P^2}\right]$$

The remaining values are written down by symmetry. Substitution of these values in the above equation gives

$$\frac{a^2\beta^2\gamma^2}{P^4}x^2y^2z^2\left[a^2\alpha^2 + b^2\beta^2 + c^2\gamma^2\right] + \frac{a^2\beta^2\gamma^2}{P^6}x^2y^2z^2$$
$$+ xyz\frac{a^2\beta^2\gamma^2}{P^4}\{(bc\alpha + ca\beta + ab\gamma)\nabla + 2xyz\left[bc\beta\gamma + ca\gamma\alpha + ab\alpha\beta\right]\}$$
$$- xyz\frac{a^2\beta^2\gamma^2}{P^6}\{\nabla(aa^2yz + b\beta^2zx + c\gamma^2xy) - 2xyz\,.\,\alpha\beta\gamma P\left[a\alpha + b\beta + c\gamma\right]\} = 0\,.$$

The whole expression divides by the factor

$$xyz\,.\,\frac{a^2\beta^2\gamma^2}{P^4};$$

effect this division, then multiply out by P^2 and reduce further by noting that $a\alpha + b\beta + c\gamma = 0$. The terms in the result containing P^2xyz as a factor are easily seen to be

$$P^2xyz\left[a^2\alpha^2 + b^2\beta^2 + c^2\gamma^2 + 2\beta\gamma bc + 2\gamma\alpha ca + 2a\beta ab\right] = P^2xyz(a\alpha + b\beta + c\gamma)^2 = 0.$$

The terms remaining are now

$$a^2\beta^2\gamma^2xyz - (aa^2yz + b\beta^2zx + c\gamma^2xy)\nabla + P^2(bcx + cay + abz)\nabla = 0\,.$$

This is the equation of a skew surface of the fifth degree. The principal section in the plane of xy is the cubic

$$(a-b)^2xy - (bx + ay)(x+y)^2 = 0\,.$$

This has an asymptote

$$bx + ay + ab = 0$$

which meets the curve in

$$ax + by = 0\,.$$

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There is further an asymptotic parabola

$$(x+y)^2 = ax + by + ab,$$

and this meets the curve in

$$x + y = -\frac{ab}{a+b}$$

$$bx + ay = \left(\frac{ab}{a+b}\right)^2.$$

The discussion of this surface is reserved for the present, but we may just notice the values of the coördinates of a point on any of the principal sections corresponding to a given value of t. We have

$$\frac{ax}{(a+t)^2} + \frac{by}{(b+t)^2} + \frac{cz}{(c+t)^2} = 1,$$

$$\frac{x}{a+t} + \frac{y}{b+t} + \frac{z}{c+t} = 0.$$

For the section in the plane $x = 0$ we may write

$$y = M(b+t), \qquad z = -M(c+t),$$

then

$$M\left(\frac{b}{b+t} - \frac{c}{c+t}\right) = 1,$$

and so

$$M = \frac{(b+t)(c+t)}{(b-c)t}.$$

Introducing this value of M we have the values of y and z corresponding to $x = 0$. Similarly the coördinates of a point in the other two planes may be given. Arranged in tabular form these are

$x = 0$	$x = -\dfrac{(c+t)(a+t)^2}{(c-a)t}$	$x = \dfrac{(a+t)^2(b+t)}{(a-b)t}$
$y = \dfrac{(b+t)^2(c+t)}{(b-c)t}$	$y = 0$	$y = -\dfrac{(a+t)(b+t)^2}{(a-b)t}$
$z = -\dfrac{(b+t)(c+t)^2}{(b-c)t}$	$z = \dfrac{(c+t)^2(a+t)}{(c-a)t}$	$z = 0$

The equations of the sections of the skew surface corresponding to these sets of values of x, y, z are

$$(b-c)^2yz - (cy+bz)(y+z)^2 = 0,$$
$$(c-a)^2zx - (az+cx)(z+x)^2 = 0,$$
$$(a-b)^2xy - (bx+ay)(x+y)^2 = 0.$$

If in the equation of the skew surface we replace x, y, z, a, b, c by the squares of these quantities we have at once the required equation of the counter-pedal. The correspondence between these two surfaces is such that to every

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generator on the ruled surface corresponds a certain curve on the counter-pedal. The curve and generator are found by giving t a certain constant value in both cases. The lines on the ellipsoid corresponding to a given value of t are readily found. Required to find the line on

$$\frac{\xi^2}{a^2}+\frac{\eta^2}{b^2}+\frac{\zeta^2}{c^2}=1$$

for which t, *i. e.* $-I^a$, has a constant value, say $-t_0$: this gives

$$\frac{\xi^2}{a^2}+\frac{\eta^2}{b^2}+\frac{\zeta^2}{c^2}=\frac{1}{t_0};$$

the required curve is then the intersection of the two ellipsoids

$$\frac{\xi^2}{a^2}+\frac{\eta^2}{b^2}+\frac{\zeta^2}{c^2}=1$$
$$\frac{t_0\xi^2}{a^2}+\frac{t_0\eta^2}{b^2}+\frac{t_0\zeta^2}{c^2}=1.$$

The projections of this curve on the coördinate planes are evidently conics; the projection on the plane of xz for example is the hyperbola

$$\frac{\xi^2}{a^2}\cdot\frac{a^2-b^2}{a^2}-\frac{\zeta^2}{c^2}\cdot\frac{b^2-c^2}{c^2}=\frac{t_0-b^2}{t_0}.$$

From their definition, these curves are obviously Poinsot's pollhodes. For the value $t_0=b^2$ the curve on the ellipsoid is the *separating* pollhode; its projection on the plane zx is the pair of lines

$$\frac{\xi^2}{a^2}\cdot\frac{a^2-b^2}{a^2}-\frac{\zeta^2}{c^2}\cdot\frac{b^2-c^2}{c^2}=0.$$

The pollhode itself consists of two ellipses whose planes pass through the axis of y. The curves on the counter-pedal corresponding to a certain constant value of t, *i. e.* $-I^a$, are found by laying off on the normals to the ellipsoid along the corresponding pollhode the length P. The extremities of these lines also lie in that parallel to the ellipsoid for which the modulus $=P$; the lines on the counter-pedal are then the intersections of the inner sheet of the parallel surface with the counter-pedal. These are only partial intersections, and I have not been able to determine the degree of the curve.

The equation of the counter-pedal is obtained from that of the skew surface as above indicated, and is

$$\begin{aligned}&\alpha^2\beta^2\gamma^2x^2y^2z^2\\&-(a^2\alpha^2y^2z^2+b^2\beta^2z^2x^2+c^2\gamma^2x^2y^2)(\alpha^2x^2+\beta^2y^2+\gamma^2z^2-2\alpha\beta xy-2\beta\gamma yz-2\gamma\alpha zx)\\&+(x^2+y^2+z^2)^2(b^2c^2\alpha^2x^2+c^2a^2\beta^2y^2+a^2b^2\gamma^2z^2)(\alpha^2x^2+\beta^2y^2+\gamma^2z^2\\&\qquad-2\beta\gamma yz-2\gamma\alpha zx-2\alpha\beta xy)=0.\end{aligned}$$

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The counter-pedal is therefore of the tenth degree—the same degree as that of the negative pedal of the ellipsoid. The terms are grouped into those of the sixth, eighth, and tenth degrees respectively. Writing

$$A = [\Sigma x^2]^2, \quad B = \Sigma a^2 x^4, \quad C = \Sigma b^2 c^2 x^2,$$
$$D = \Sigma a^2 \alpha^2 y^2 z^2, \quad E = 2\Sigma \alpha\beta x^2 y^2, \quad G = a^2\beta^2\gamma^2 x^2 y^2 z^2,$$

the equation may be written

$$G + (B - E)(AC - D) = 0,$$

or, writing

$$B - E = -L, \qquad AC - D = M,$$

the equation is

$$G - LM = 0.$$

The L is the ∇ of the above. For $G = 0$ with $M = 0$ we have the principal sections of the surface—complete in the planes $z = 0$ and $x = 0$, but as we shall see not complete in $y = 0$. These principal sections are the counter-pedals of the principal sections of the ellipsoid together with, in the plane $y = 0$, a certain pair of straight lines. The equations of the counter-pedals of the principal ellipses are

$$(b^2 - c^2)^2 y^2 z^2 - (c^2 y^2 + b^2 z^2)(y^2 + z^2)^2 = 0,$$
$$(c^2 - a^2)^2 z^2 x^2 - (a^2 z^2 + c^2 x^2)(z^2 + x^2)^2 = 0,$$
$$(a^2 - b^2)^2 x^2 y^2 - (b^2 x^2 + a^2 y^2)(x^2 + y^2)^2 = 0.$$

The coördinates of a point on each of these sextic curves are given by the table

$x^2 = 0$	$x^2 = -\dfrac{(c^2+t)(a^2+t)^2}{(c^2-a^2)t}$	$x^2 = \dfrac{(a^2+t)^2(b^2+t)}{(a^2-b^2)t}$
$y^2 = \dfrac{(b^2+t)^2(c^2+t)}{(b^2-c^2)t}$	$y^2 = 0$	$y = -\dfrac{(a^2+t)(b^2+t)^2}{(a^2-b^2)t}$
$z^2 = -\dfrac{(b^2+t)(c^2+t)^2}{(b^2-c^2)t}$	$z^2 = \dfrac{(c^2+t)^2(a^2+t)}{(c^2-a^2)t}$	$z = 0$

It is important to notice that these values go in pairs. For values of $-t < b^2$ the first and second columns give real values of x, y and z, while the third gives imaginary values; for $-t = b^2$ the first and third columns vanish; for values of $-t > b^2$ the first column is imaginary while the second and third are real. This remark is important in making a drawing or model of the surface, as it shows just what points in the three cross sections are to be united.

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[illegible]

[illegible]

$$z = \quad : \quad = 1$$

[illegible]

$$x^2 - z^2 = 1 \quad : \quad = 1$$
$$z^2 - y^2 = 1 \quad : \quad = 1$$
$$x^2 - y^2 = 1 \quad : \quad = 1$$

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$$x^2 - z^2 = 1$$

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z

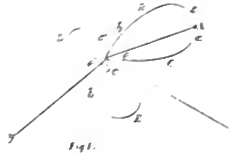

Fig 1.

The portion OBA of the loop in the plane $y = 0$ corresponds to values of t between $-D$ and $-\sigma$ and is joined to the corresponding points in the loop E; the values of the corresponding points in OBA and E are found from the above table. The portion OCA is joined in like manner to D. The small letters indicate corresponding points and serve to show completely how a drawing or model of the surface may be constructed.

In making a drawing of the surface it will of course be desirable to work out the numerical values of a few of the corresponding points though the lines joining them will have to be filled in by the eye—unless indeed one chooses to go through a very tedious computation to find the intermediate points through which to trace them.

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The lines

$$\alpha x^3 - \gamma z^3 = 0$$

are clearly double lines on the surface; a section of the surface through the point a of Fig. 1 will consist of two curves like Fig. 2.

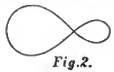

Fig. 2.

This section gives only eight real points of intersection with a right line. There are four real singular points of the nature of triple points in the plane of $y = 0$ and an equal number of imaginary ones in the other two planes; the origin is a singular point of a very high order and will hardly repay study. The double lines

$$\alpha x^3 - \gamma z^3 = 0$$

on the counter-pedal correspond to the separating pollhode on the ellipsoid; the projection of these lines has been shown to be

$$\frac{x^2}{a^2} \cdot \frac{\gamma}{a^2} - \frac{z^2}{c^2} \cdot \frac{\alpha}{c^2} = 0;$$

the angle between these projections and the double lines being called θ, we have

$$\cos\theta = (a^2 + c^2)\sqrt{a\gamma} \div \sqrt{a\gamma(a^4 + c^4) + a^4c^4 + c^4\gamma^2}.$$

This is a right angle only for ellipsoids of revolution, as we can only have $\cos\theta = 0$ for $\alpha = 0$ or $\gamma = 0$. The projection and the double line will coincide with each other for $\cos\theta = 1$; this gives

$$b^2 = c^2\,\frac{a^2 - c^2}{a^2 + c^2}.$$

The double lines are at right angles for an ellipsoid whose axes are connected by the relation

$$b^2 = \frac{2a^2c^2}{a^2 + c^2}.$$

I thought that the umbilics of the ellipsoid might correspond to the above mentioned triple points or the counter-pedal; on testing I found that they did not correspond, though there is a singular relation between the coördinates of the points corresponding to the umbilics and the coördinates of the triple points.

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The coördinates of the umbilics on the ellipsoid are

$$x^2 = -a^2\frac{\gamma}{\beta}, \quad y = 0, \quad z^2 = -c^2\frac{\alpha}{\beta};$$

the value of t for these points is $-\frac{c^2+a^2}{2}$; substituting this in the second column of the above table we have

$$x^2 = -\frac{\gamma a^2}{b^2\beta}, \quad y = 0, \quad z^2 = -\frac{\alpha c^2}{b^2\beta}.$$

The coördinates of the triple points on the counter-pedal are found by making $t = -b^2$; they are

$$x^2 = -\frac{\gamma a^2}{b^2\beta}, \quad y = 0, \quad z^2 = -\frac{\alpha c^2}{b^2\beta}.$$

The values of x and z for the two series of points are just interchanged. The condition that the umbilics on the ellipsoid should correspond to the triple points on the counter-pedal is

$$b^2 = \frac{a^2+c^2}{2}.$$

Besides the two straight double lines on the surface there are two other double lines whose projections are of a quadrifoil shape, the curves in space having the same shape only bent to fit the surface.

The existence of these lines is readily inferred from Fig. 1; they are produced by the intersection of the portion of the surface joining the loop E to the partial loop OBA with the portion which joins the loop D to the partial loop OCA. The degree of these nodal lines I have not been able to determine.

The lines of curvature on the counter-pedal to the ellipsoid are its intersections with the counter-pedals to the two confocal hyperholoids. I have not been able to deduce any results of consequence concerning the curvature of this surface, but in the next few pages I have given the values of all of the quantities employed by Gauss in his investigations on the curvature of surfaces. These values will certainly be necessary in any future study of the curvature of the counter-pedal, so it is worth while giving them here, although I have not been able to determine in a simple manner the radii of curvature.

Denoting by u and v the curvilinear coördinates of a point on the surface of the ellipsoid, we have

$$-\beta\gamma\xi^2 = a^2(a^2+u)(a^2+v),$$
$$-\gamma\alpha\eta^2 = b^2(b^2+u)(b^2+v),$$
$$-\alpha\beta\zeta^2 = c^2(c^2+u)(c^2+v).$$

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Let P, P_1, P_2 denote the three perpendiculars from the centre upon the tangent planes to the three confocal quadrics at their common point ξ, η, ζ, then

$$\frac{1}{P^2} = \frac{\xi^2}{a^4} + \frac{\eta^2}{b^4} + \frac{\zeta^2}{c^4},$$

$$\frac{1}{P_1^2} = \frac{\xi^2}{(a^2+u)^2} + \frac{\eta^2}{(b^2+u)^2} + \frac{\zeta^2}{(c^2+u)^2},$$

$$\frac{1}{P_2^2} = \frac{\xi^2}{(a^2+v)^2} + \frac{\eta^2}{(b^2+v)^2} + \frac{\zeta^2}{(c^2+v)^2};$$

or in terms of u and v these are

$$P^2 = \frac{a^2b^2c^2}{uv},$$

$$P_1^2 = \frac{(a^2+u)(b^2+u)(c^2+u)}{u(u-v)},$$

$$P_2^2 = \frac{(a^2+v)(b^2+v)(c^2+v)}{v(v-u)}.$$

The element of length ds given in the form

$$\sqrt{Edu^2 + 2Fdudv + Gdv^2}$$

is of course for the ellipsoid

$$= \frac{1}{2}\sqrt{\frac{du^2}{P_1^2} + \frac{dv^2}{P_2^2}}.$$

Denote by $\mathcal{E}$, $\mathcal{F}$, $\mathcal{G}$ the quantities which on the counter-pedal correspond to E, F, G on the original surface: then

$$\mathcal{E} = \left(\frac{dx}{du}\right)^2 + \left(\frac{dy}{du}\right)^2 + \left(\frac{dz}{du}\right)^2$$

$$\mathcal{F} = \frac{dx}{du}\frac{dx}{dv} + \frac{dy}{du}\frac{dy}{dv} + \frac{dz}{du}\frac{dz}{dv}$$

$$\mathcal{G} = \left(\frac{dx}{dv}\right)^2 + \left(\frac{dy}{dv}\right)^2 + \left(\frac{dz}{dv}\right)^2.$$

Now

$$x = \xi\left(1 - \frac{P^2}{a^2}\right) \&c.$$

and therefore

$$\frac{dx}{du} = \frac{d\xi}{du} - \frac{P^2}{a^2}\frac{d\xi}{du} - \frac{\xi}{a^2}\frac{dP^2}{du} \&c.$$

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Substituting in the expression for $\mathcal{I}$ we have

$$\mathcal{I} = \Sigma\left(\frac{d\xi}{du}\right)^2 - 2I^2\Sigma\frac{1}{a^2}\left(\frac{d\xi}{du}\right)^2 - 2\frac{dP^2}{du}\Sigma\frac{\xi}{a^2}\frac{d\xi}{du}$$
$$+ 2I^2\frac{dP^2}{du}\Sigma\frac{\xi}{a^4}\frac{d\xi}{du} + I^4\Sigma\frac{1}{a^4}\left(\frac{d\xi}{du}\right)^2 + \left(\frac{dP^2}{du}\right)^2\Sigma\frac{\xi^2}{a^4}.$$

To reduce this, observe that

$$\frac{d\xi}{du} = \frac{1}{2}\frac{\xi}{a^2+u}, \text{ \&c.}$$

$$\Sigma\frac{\xi}{a^2}\frac{d\xi}{du} = 0,$$

$$\Sigma\frac{\xi^2}{a^2(a^2+u)^2} = -\frac{1}{uP_1^2}, \quad \Sigma\frac{\xi^2}{a^4(a^2+u)} = \frac{1}{uP^2},$$

$$\Sigma\frac{\xi^2}{a^4(a^2+u)^2} = \frac{1}{u^2}\frac{P^2+P_1^2}{P^2P_1^2}, \quad \frac{dP^2}{du} = -\frac{P_1^2}{u}, \quad \left(\frac{dP}{du}\right)^2 = \frac{1}{4}\frac{P^2}{u^2}.$$

Making these and other obvious reductions we have

$$\mathcal{I} = E + \frac{P^2}{2uP_1^2} + \frac{P^2(P^2+P_1^2)}{4uP_1^2}$$

or

$$\mathcal{I} = E + \frac{P^2}{4u^2P_1^2}\left[I^2 + 2u + I_1^2\right];$$

of course it follows from the symmetry of $\mathcal{I}$ and $\mathcal{D}$ that

$$\mathcal{D} = G + \frac{P^2}{4v^2P_2^2}\left[I^2 + 2v + I_2^2\right].$$

The reductions to be performed in order to find $\mathcal{A}$ are a little different from the above, but there is no difficulty in getting it; all three of these quantities may be written as follows:

$$\mathcal{I} = \frac{P^2}{4P_1^2}\left(\frac{1}{P} + \frac{P}{u}\right)^2 + \frac{1}{4}\frac{P^2}{u^2},$$

$$\mathcal{D} = \frac{P^2}{4P_2^2}\left(\frac{1}{P} + \frac{P}{v}\right)^2 + \frac{1}{4}\frac{P^2}{v^2},$$

$$\mathcal{A} = \frac{1}{4}\frac{P^2}{a^2b^2c^2}, \quad = \frac{1}{4}\frac{P^2}{uv}.$$

The element of length on the counter-pedal being now given by

$$d\sigma^2 = \mathcal{I}du^2 + 2\mathcal{A}dudv + \mathcal{D}dv^2$$

becomes

$$d\sigma^2 = \frac{P^2}{4}\left\{\left[\left(\frac{1}{P} + \frac{P}{u}\right)\frac{du}{P_1}\right]^2 + \left[\left(\frac{1}{P} + \frac{P}{v}\right)\frac{dv}{P_2}\right]^2 + \left(\frac{du}{u} + \frac{dv}{v}\right)^2\right\}.$$

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The element of area of the counter-pedal is

$$d\Sigma = \sqrt{EG - F^2}\,dudv, \; = Ududv.$$

Now

$$U^2 = \frac{P^4}{16P_1^2P_2^2}\left\{\left(\frac{1}{P}+\frac{P}{u}\right)^2\left(\frac{1}{P}+\frac{P}{v}\right)^2 + \frac{P_2^2}{v^2}\left(\frac{1}{P}+\frac{P}{u}\right)^2 + \frac{P_1^2}{u^2}\left(\frac{1}{P}+\frac{P}{v}\right)^2\right\}.$$

This is easily brought into the form

$$U^2 = \frac{1}{16}\frac{(P^2+u)^2(P^2+v)^2}{P_1^2P_2^2u^2v^2}\left[1+\frac{P^2P_1^2}{(P^2+u)^2}+\frac{P^2P_2^2}{(P^2+v)^2}\right],$$

or again

$$U^2 = \frac{1}{16}\frac{1}{P_1^2P_2^2}\left[\frac{(P^2+u)^2(P^2+v)^2}{u^2v^2}+\frac{P^2P_1^2(P^2+v)^2}{u^2v^2}+\frac{P^2P_2^2(P^2+u)^2}{u^2v^2}\right],$$

or say

$$U^2 = \frac{1}{16}\frac{T^2}{P_1^2P_2^2};$$

the element of area is now

$$d\Sigma = \frac{1}{4}\frac{T}{P_1P_2}dudv,$$

and for the total area we must have

$$\Sigma = 2\int_{-a^2}^{-b^2}\int_{-b^2}^{-c^2}\frac{T}{P_1P_2}dudv;$$

of course the area of the ellipsoid is

$$S = 2\int_{-a^2}^{-b^2}\int_{-b^2}^{-c^2}\frac{dudv}{P_1P_2}.$$

The ratio between corresponding elements of area on the ellipsoid and its counter-pedal is

$$\frac{d\Sigma}{dS} = T.$$

Denoting by $(\alpha_1, \beta_1, \gamma_1)$ and $(\alpha_2, \beta_2, \gamma_2)$ the direction-cosines of the normals to the ellipsoid and counter-pedal respectively at corresponding points, we have

$$T = \begin{vmatrix} \alpha_2, & \frac{dx}{d\xi}, & \frac{dx}{d\eta}, & \frac{dx}{d\zeta} \\ \beta_2, & \frac{dy}{d\xi}, & \frac{dy}{d\eta}, & \frac{dy}{d\zeta} \\ \gamma_2, & \frac{dz}{d\xi}, & \frac{dz}{d\eta}, & \frac{dz}{d\zeta} \\ 0 & \alpha_1 & \beta_1 & \gamma_1 \end{vmatrix}.$$

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The verification of the value of T by working out the determinant would be a very different matter in the case of $\mathbf{r}_{ss}$, $\mathbf{r}_{sss}$. Various ingenious devices for the reduction of the number of the terms in the determinant have been extensively employed.

Using the notation employed in Chapter VIII, if three functions, ϕ, ψ, χ, of s are defined by the equations

$$\phi = \frac{dx}{ds}\frac{d^2x}{ds^2} + \frac{dy}{ds}\frac{d^2y}{ds^2} + \frac{dz}{ds}\frac{d^2z}{ds^2},$$

$$\psi = \frac{dx}{ds}\frac{d^3x}{ds^3} + \frac{dy}{ds}\frac{d^3y}{ds^3} + \frac{dz}{ds}\frac{d^3z}{ds^3},$$

$$\chi = \left(\frac{d^2x}{ds^2}\right)^2 + \left(\frac{d^2y}{ds^2}\right)^2 + \left(\frac{d^2z}{ds^2}\right)^2,$$

then the direction-cosines α, β, γ of the principal normal are given by the equations

$$\alpha = \frac{1}{\sqrt{\chi}}\left(\frac{d^2x}{ds^2} - \frac{\phi}{\chi}\frac{dx}{ds}\right), \quad \beta = \frac{1}{\sqrt{\chi}}\left(\frac{d^2y}{ds^2} - \frac{\phi}{\chi}\frac{dy}{ds}\right), \quad \gamma = \frac{1}{\sqrt{\chi}}\left(\frac{d^2z}{ds^2} - \frac{\phi}{\chi}\frac{dz}{ds}\right).$$

The curvature K is given by the equation

$$K = \sqrt{\chi - \phi^2},$$

and the torsion T by the equation

$$T = \frac{1}{K^2}\begin{vmatrix} \frac{dx}{ds} & \frac{dy}{ds} & \frac{dz}{ds} \\ \frac{d^2x}{ds^2} & \frac{d^2y}{ds^2} & \frac{d^2z}{ds^2} \\ \frac{d^3x}{ds^3} & \frac{d^3y}{ds^3} & \frac{d^3z}{ds^3} \end{vmatrix}.$$

Here the value of ϕ is $-\frac{1}{2}\frac{d\chi}{ds}$, and the value of χ is $\frac{1}{a^2}\left(1 - \frac{x^2}{a^2}\right) + \frac{1}{b^2}\left(1 - \frac{y^2}{b^2}\right) + \frac{1}{c^2}\left(1 - \frac{z^2}{c^2}\right)$.

We find now at once

$$T = \frac{1}{K^2}\left\{\frac{x}{a^2}\begin{vmatrix} \frac{dy}{ds} & \frac{dz}{ds} \\ \frac{d^2y}{ds^2} & \frac{d^2z}{ds^2} \end{vmatrix} + \frac{y}{b^2}\begin{vmatrix} \frac{dz}{ds} & \frac{dx}{ds} \\ \frac{d^2z}{ds^2} & \frac{d^2x}{ds^2} \end{vmatrix} - \frac{z}{c^2}\begin{vmatrix} \frac{dx}{ds} & \frac{dy}{ds} \\ \frac{d^2x}{ds^2} & \frac{d^2y}{ds^2} \end{vmatrix}\right\},$$

or

$$T = -\frac{1}{K^2}\begin{vmatrix} -\frac{x}{a^2}, & -\frac{y}{b^2}, & -\frac{z}{c^2} \\ \frac{dx}{ds}, & \frac{dy}{ds}, & \frac{dz}{ds} \\ \frac{d^2x}{ds^2}, & \frac{d^2y}{ds^2}, & \frac{d^2z}{ds^2} \end{vmatrix}$$

$$= -\frac{1}{K^2}\begin{vmatrix} -\left(\frac{1}{a^2} + \frac{1}{a^2} + \frac{1}{b^2} + \frac{1}{c^2}\right), & \frac{1}{b^2}\left(1 + \frac{1}{a^2}\right), & \frac{1}{c^2}\left(1 + \frac{1}{a^2}\right) \\ \frac{dx}{ds}, & \frac{dy}{ds}, & \frac{dz}{ds}, \\ \frac{d^2x}{ds^2}, & \frac{d^2y}{ds^2}, & \frac{d^2z}{ds^2}. \end{vmatrix}$$

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or finally

$$V = A - \begin{vmatrix} \frac{-k}{b^2c^2}\left(b^2+c^2\right), & \frac{\eta}{b^2}, & \frac{\zeta}{c^2} \\ \frac{dk}{du}, & \frac{d\eta}{du}, & \frac{d\zeta}{du} \\ \frac{dk}{dv}, & \frac{d\eta}{dv}, & \frac{d\zeta}{dv} \end{vmatrix} - \frac{k}{b^2c^2}\begin{vmatrix} -k, & \eta, & \zeta \\ \frac{dk}{du}, & \frac{d\eta}{du}, & \frac{d\zeta}{du} \\ \frac{dk}{dv}, & \frac{d\eta}{dv}, & \frac{d\zeta}{dv} \end{vmatrix}.$$

The values of H and Θ may of course be written down at once by symmetry.

There are three other quantities necessary in obtaining the expressions for the radii of curvature, &c., by Gauss's method, viz.

$$\mathcal{E}' = \begin{vmatrix} \frac{d^2x}{du^2}, & \frac{d^2y}{du^2}, & \frac{d^2z}{du^2} \\ \frac{dx}{du}, & \frac{dy}{du}, & \frac{dz}{du} \\ \frac{dx}{dv}, & \frac{dy}{dv}, & \frac{dz}{dv} \end{vmatrix} \text{ &c.,}$$

or

$$\mathcal{E}' = \frac{d^2x}{du^2}V + \frac{d^2y}{du^2}H + \frac{d^2z}{du^2}\Theta$$

$$\mathcal{F}' = \frac{d^2x}{dudv}V + \frac{d^2y}{dudv}H + \frac{d^2z}{dudv}\Theta$$

$$\mathcal{G}' = \frac{d^2x}{dv^2}V + \frac{d^2y}{dv^2}H + \frac{d^2z}{dv^2}\Theta.$$

The values of these expressed as determinants of the fourth order are easily found; they are

$$\mathcal{E}' = \begin{vmatrix} \frac{abc}{}, & \frac{-bc}{a^2}\xi, & \frac{-ca}{b^2}\eta, & \frac{-ab}{c^2}\zeta \\ \frac{d^2k}{du^2}, & \frac{d^2\xi}{du^2}, & \frac{d^2\eta}{du^2}, & \frac{d^2\zeta}{du^2} \\ \frac{dk}{du}, & \frac{d\xi}{du}, & \frac{d\eta}{du}, & \frac{d\zeta}{du} \\ \frac{dk}{dv}, & \frac{d\xi}{dv}, & \frac{d\eta}{dv}, & \frac{d\zeta}{dv} \end{vmatrix} + 2\frac{dk}{du}\left\{\frac{1}{a^2}\frac{d\xi}{du}V + \frac{1}{b^2}\frac{d\eta}{du}H + \frac{1}{c^2}\frac{d\zeta}{du}\Theta\right\}.$$

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We may now write

$$\mathcal{H} = E + \frac{1}{\rho_1}\frac{\partial x}{\partial \rho_1}\frac{\partial \bar{x}}{\partial \rho_1} + \frac{1}{\rho_2}\frac{\partial x}{\partial \rho_2}\frac{\partial \bar{x}}{\partial \rho_2} - \begin{vmatrix} -\bar{x} & \frac{\partial x}{\partial \rho_1} & \frac{\partial x}{\partial \rho_2} & \frac{\partial \bar{x}}{\partial \rho_1} \\ \frac{\partial \bar{x}}{\partial \rho_1} & \frac{\partial^2 x}{\partial \rho_1^2} & \frac{\partial^2 x}{\partial \rho_1 \partial \rho_2} & \frac{\partial^2 \bar{x}}{\partial \rho_1^2} \\ \frac{\partial \bar{x}}{\partial \rho_2} & \frac{\partial^2 x}{\partial \rho_1 \partial \rho_2} & \frac{\partial^2 x}{\partial \rho_2^2} & \frac{\partial^2 \bar{x}}{\partial \rho_1 \partial \rho_2} \\ \frac{\partial x}{\partial \rho_1} & \frac{\partial^2 \bar{x}}{\partial \rho_1^2} & \frac{\partial^2 \bar{x}}{\partial \rho_1 \partial \rho_2} & \frac{\partial^2 x}{\partial \rho_1^2} \\ \frac{\partial x}{\partial \rho_2} & \frac{\partial^2 \bar{x}}{\partial \rho_1 \partial \rho_2} & \frac{\partial^2 \bar{x}}{\partial \rho_2^2} & \frac{\partial^2 x}{\partial \rho_1 \partial \rho_2} \end{vmatrix} \div \begin{vmatrix} \frac{\partial x}{\partial \rho_1} & \frac{\partial \bar{x}}{\partial \rho_1} \\ \frac{\partial x}{\partial \rho_2} & \frac{\partial \bar{x}}{\partial \rho_2} \end{vmatrix}$$

The expression for G may be written down by symmetry: that for $\mathcal{F}$ is

$$\mathcal{F} = \frac{\partial x}{\partial \rho_1}\frac{\partial \bar{x}}{\partial \rho_2}\frac{1}{\rho_1}\frac{\partial \bar{x}}{\partial \rho_1} + \frac{\partial x}{\partial \rho_2}\frac{\partial \bar{x}}{\partial \rho_2}\frac{1}{\rho_2}\frac{\partial \bar{x}}{\partial \rho_2} - \begin{vmatrix} -\bar{x} & \frac{\partial \bar{x}}{\partial \rho_1} & \frac{\partial \bar{x}}{\partial \rho_2} & \frac{\partial x}{\partial \rho_1} \\ \frac{\partial \bar{x}}{\partial \rho_1} & \frac{\partial^2 \bar{x}}{\partial \rho_1^2} & \frac{\partial^2 \bar{x}}{\partial \rho_1 \partial \rho_2} & \frac{\partial^2 x}{\partial \rho_1^2} \\ \frac{\partial \bar{x}}{\partial \rho_2} & \frac{\partial^2 \bar{x}}{\partial \rho_1 \partial \rho_2} & \frac{\partial^2 \bar{x}}{\partial \rho_2^2} & \frac{\partial^2 x}{\partial \rho_1 \partial \rho_2} \\ \frac{\partial x}{\partial \rho_1} & \frac{\partial^2 x}{\partial \rho_1^2} & \frac{\partial^2 x}{\partial \rho_1 \partial \rho_2} & \frac{\partial^2 \bar{x}}{\partial \rho_1^2} \\ \frac{\partial x}{\partial \rho_2} & \frac{\partial^2 x}{\partial \rho_1 \partial \rho_2} & \frac{\partial^2 x}{\partial \rho_2^2} & \frac{\partial^2 \bar{x}}{\partial \rho_1 \partial \rho_2} \end{vmatrix} \div \begin{vmatrix} \frac{\partial \bar{x}}{\partial \rho_1} & \frac{\partial x}{\partial \rho_1} \\ \frac{\partial \bar{x}}{\partial \rho_2} & \frac{\partial x}{\partial \rho_2} \end{vmatrix}.$$

I have not been able to simplify these expressions in any satisfactory manner.

If we denote by $\bar{x}, \bar{y}, \bar{z}$ the coördinates of a point on the pedal of the n^{th} pedal, it is easy to see that

$$\xi = x - x\frac{\partial \bar{x}}{\partial x} - y\frac{\partial \bar{x}}{\partial y} - z\frac{\partial \bar{x}}{\partial z}, \quad \eta = y - x\frac{\partial \bar{y}}{\partial x} - y\frac{\partial \bar{y}}{\partial y} - z\frac{\partial \bar{y}}{\partial z}, \quad \zeta = z - x\frac{\partial \bar{z}}{\partial x} - y\frac{\partial \bar{z}}{\partial y} - z\frac{\partial \bar{z}}{\partial z}$$

or

$$x = \xi - \bar{x}, \quad y = \eta - \bar{y}, \quad z = \zeta - \bar{z}.$$

If E_1, F_1, G_1 refer to the pedal, we have for the element of length on that surface

$$ds^2 = E_1 d\rho_1^2 + 2F_1 d\rho_1 d\rho_2 + G_1 d\rho_2^2.$$

It is easy to show that

$$E_1 = E + \bar{E} + \frac{P^2}{\rho_1 \rho_1'},$$

$$G_1 = G + \bar{G} + \frac{P^2}{\rho_2 \rho_2'},$$

$$F_1 = F,$$

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and then for the element of length on the counter-pedal

$$d\bar{\sigma}^2 = ds^2 + d\bar{\sigma}^2 + \frac{P^2}{2}\left(\frac{du^2}{uP_1^2} + \frac{dv^2}{vP_2^2}\right);$$

writing

$$\Lambda^2 = a^2b^2c^2,$$
$$\Lambda_1^2 = a^2 + u \cdot b^2 + u \cdot c^2 + u,$$
$$\Lambda_2^2 = a^2 + v \cdot b^2 + v \cdot c^2 + v,$$

the last term in $d\sigma^2$ becomes

$$\frac{P^2}{2}(u-v)\left[\frac{du^2}{\Lambda_1^2} - \frac{dv^2}{\Lambda_2^2}\right],$$

$$= \frac{\Lambda^2}{2}\left(\frac{1}{v} - \frac{1}{u}\right)\left[\frac{du^2}{\Lambda_1^2} - \frac{dv^2}{\Lambda_2^2}\right];$$

and so

$$d\bar{\sigma}^2 = ds^2 + d\bar{\sigma}^2 + \frac{\Lambda^2}{2}\left(\frac{1}{v} - \frac{1}{u}\right)\left[\frac{du^2}{\Lambda_1^2} - \frac{dv^2}{\Lambda_2^2}\right].$$

It would be interesting to find an interpretation of this last term, but I see no means of doing it.

Denoting by $d\bar{\Sigma}$ the element of area on the pedal, we have

$$d\bar{\Sigma} = \sqrt{EG - F^2}\,du\,dv;$$

also

$$\bar{E} = \frac{P^2}{4u^2} \cdot \frac{P^2 + P_1^2}{P_1^2},$$

$$\bar{G} = \frac{P^2}{4v^2} \cdot \frac{P^2 + P_2^2}{P_2^2},$$

$$\bar{F} = \frac{1}{4} \cdot \frac{P^2}{uv};$$

calling the quantity under the radical sign $\bar{V}^2$ we have

$$\bar{V}^2 = \frac{P^6}{16u^2v^2P_1^2P_2^2}\left[I^4 + I_1^4 + I_2^4\right],$$

and for the ratio between the elements of area of the pedal and counter-pedal

$$\frac{U}{\bar{V}} = \frac{\sqrt{}(P^2+u)^2(P^2+v)^2 + P^2P_1^2(P^2+v)^2 + P^2P_2^2(P^2+u)^2}{I^4\sqrt{I^2 + P_1^2 + P_2^2}}.$$

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Calling α_2, β_2, γ_2 and $\overline{\alpha_2}$, $\overline{\beta_2}$, $\overline{\gamma_2}$ the direction-cosines of the norma.: at corresponding points to the counter-pedal and pedal respectively, this ratio is the value of the determinant

$$\begin{vmatrix} \alpha_2 & \frac{dx}{dx} & \frac{dx}{dy} & \frac{dx}{dz} \\ \beta_2 & \frac{dy}{dx} & \frac{dy}{dy} & \frac{dy}{dz} \\ \gamma_2 & \frac{dz}{dx} & \frac{dz}{dy} & \frac{dz}{dz} \\ & \overline{\alpha_2} & \overline{\beta_2} & \overline{\gamma_2} \end{vmatrix}.$$

Let $F(\xi, \eta, \zeta) = 0$ represent any surface, and denote by F_ξ, F_η, F_ζ the derivatives of F with respect to ξ, η, ζ. The equation of the tangent plane to this surface is (x', y', z' denoting current coördinates in the plane)

$$(x-\xi)F_\xi + (y-\eta)F_\eta + (z-\zeta)F_\zeta = 0;$$

taking the origin as the pole we have for the perpendicular upon the tangent plane

$$p = -\frac{\xi F_\xi + \eta F_\eta + \zeta F_\zeta}{Q},$$

where $$Q^2 = F_\xi^2 + F_\eta^2 + F_\zeta^2.$$

The direction-cosines of the normal, and therefore of p, are

$$\frac{F_\xi}{Q}, \quad \frac{F_\eta}{Q}, \quad \frac{F_\zeta}{Q};$$

and the coördinates of a point on the pedal surface are

$$\overline{x}, \overline{y}, \overline{z} = \frac{pF_\xi}{Q}, \quad \frac{pF_\eta}{Q}, \quad \frac{pF}{Q}.$$

Writing $\frac{p}{Q} = k$ we have for the coördinates of a point on the counter-pedal

$$\begin{aligned} x &= \xi + kF_\xi, \\ y &= \eta + kF_\eta, \\ z &= \zeta + kF_\zeta. \end{aligned}$$

The elimination of ξ, η, ζ between these equations and $F = 0$ will give the equation of the counter-pedal of $F = 0$.

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Write the coördinates x, y, z in the form

$$x = \xi + \bar{x}, \quad y = \eta + \bar{y}, \quad z = \zeta + \bar{z}$$

and we have for $\mathcal{I}$, $\mathcal{J}$, $\mathcal{D}$ the general values

$$\mathcal{I} = E + \bar{E} + 2\Sigma \frac{d\xi}{du}\frac{d\bar{x}}{du} \text{ &c.}$$

the quantities $\frac{d\xi}{du}, \frac{d\eta}{du}, \frac{d\zeta}{du}$ are proportional to the direction-cosines of the tangent to the curve $u = \text{const.}$ traced on the original surface; and $\frac{d\bar{x}}{du}, \frac{d\bar{y}}{du}, \frac{d\bar{z}}{du}$ are proportional to the direction-cosines of the tangent to the corresponding curve $u = \text{const.}$ traced on the pedal; calling θ the angle between these two tangents the above value of $\mathcal{I}$ is

$$\mathcal{I} = E + \bar{E} + 2\sqrt{E\bar{E}}\cos\theta.$$

Writing $\theta_1 = (u, \bar{u})$, we may also write

$$\theta_2 = (v, \bar{v}), \quad \phi_1 = (u, \bar{v}), \quad \phi_2 = (\bar{u}, v).$$

The whole set of values is then

$$\mathcal{I} = E + \bar{E} + 2\sqrt{E\bar{E}}\cos\theta_1,$$
$$\mathcal{J} = F + \bar{F} + 2\sqrt{E\bar{G}}\cos\phi_1 + 2\sqrt{\bar{E}G}\cos\phi_2,$$
$$\mathcal{D} = G + \bar{G} + 2\sqrt{G\bar{G}}\cos\theta_2.$$

It would be interesting to find the surfaces for which the square of the element of length on the counter-pedal is equal to the sum of the squares of the corresponding elements on the given surface and the pedal, *i. e.* the surfaces which give the relation

$$\mathcal{I}du^2 + 2\mathcal{J}dudv + \mathcal{D}dv^2 = Edu^2 + 2Fdudv + Gdv^2 + \bar{E}du^2 + 2\bar{F}dudv + \bar{G}dv^2$$

or

$$d\sigma^2 = ds^2 + d\bar{\sigma}^2.$$

The conditions for this are obviously

$$\cos\theta_1 = 0, \quad \cos\theta_2 = 0$$

and

$$\sqrt{E\bar{G}}\cos\phi_1 + \sqrt{\bar{E}G}\cos\phi_2 = 0;$$

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or otherwise

$$\Sigma \frac{d\xi}{du}\frac{d\bar{x}}{du} = 0, \quad \Sigma \frac{d\xi}{dv}\frac{d\bar{x}}{dv} = 0$$

$$\Sigma \frac{d\xi}{du}\frac{d\bar{x}}{dv} + \Sigma \frac{d\xi}{dv}\frac{d\bar{x}}{du} = 0.$$

The quantities V, H, Ω may be written in the form

$$V = A + \bar{A} - \left\{ \frac{d(\gamma, z)}{d(u, v)} - \frac{d(\zeta, \bar{y})}{d(u, v)} \right\}$$

$$H = B + \bar{B} - \left\{ \frac{d(\zeta, \bar{x})}{d(u, v)} - \frac{d(\xi, z)}{d(u, v)} \right\}$$

$$\Omega = C + \bar{C} - \left\{ \frac{d(\xi, \bar{y})}{d(u, v)} - \frac{d(\gamma, \bar{x})}{d(u, v)} \right\}.$$

There are many other general formulas that one might write down, but it is hardly worth while to do so.

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Tables for the Binary Sextic.

The Leading Coefficients of the First 18 *of the* 26 *Covariants.*

By Professor Cayley.

Including the sextic itself, the number of covariants of the binary sextic is = 26, as shown in the table p. 296 of Clebsch's "Theorie der binären algebraischen Formen," Leipzig 1872; viz. this is

Deg. \ Order.	0	2	4	6	8	10	12
1				f			
2	A		i		H		
3		l		p	(f, i)		T
4	B		$(f, l)_2$	(f, l)		(H, i)	
5		$(i, l)_2$	(i, l)		(H, l)		
6	A_{11}			(p, l) $((f, i), l)_2$			
7		$(f, l^2)_4$	$(f, l^2)_3$				
8		$(i, l^2)_3$					
9			$((f, i), l^2)_4$				
10	$(f, l^2)_6$	$(f, l^2)_5$					
12		$((f, i), l^2)_6$					
15	$((f, i), l^4)_8$						

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we have

$$\begin{aligned} S,\ \text{Coeff. } x^2 &= a\varepsilon - b\delta + c\gamma - d\beta + e\alpha, \\ T,\ \text{“ } x^4 &= a\delta - 2b\gamma + 3c\beta - 4d\alpha, \\ U,\ \text{“ } x^3 &= 2a'\delta - \beta'\gamma + \gamma'\beta - 2\delta'\alpha, \\ V,\ \text{“ } x^4 &= 280a''\varepsilon - 35\beta''\delta + 10\gamma''\gamma - 20\delta''\beta + 24\varepsilon''\alpha. \end{aligned}$$

Similarly the invariant W and the leading coefficients of X, Y depend on the coefficients of A, G and E^2; and the invariant Z depends on the coefficients of G and E^4. But these two invariants W and Z have been already calculated; viz., as already mentioned, W is Salmon's invariant D, and Z his invariant E, given each of them in the second edition of his Higher Algebra (but not reproduced in the third edition): on account of the great length of these expressions it has been thought that it was not expedient to give them here.

For the reason appearing above, I have added the expressions for the remaining coefficients of C, E, G.

$A,\ x^6$	$B,\ x^5$	$C,\ x^4$	$D,\ x^3$	$E,\ x^2$	$F,\ x^1$	$G,\ x^0$	$H,\ x^{12}$
$a+1$	$ag + 1$	$ae + 1$	$ac + 1$	$aeg + 1$	$ace + 1$	$a^2f + 1$	$a^2d + 1$
	$a^2bf - 6$	$a^2bd - 4$	$a^2b^2 - 1$	$adf - 3$	$ad^2 - 1$	$abe - 5$	$abc - 3$
	$ce + 15$	$c^2 + 3$		$c^2 + 2$	$a^2b^2e - 1$	$cd + 2$	$a^2b^2 + 2$
	$d^2 - 10$			$a^2b^2g - 1$	$bcd + 2$	$a^2b^2d + 8$	
				$bcf + 3$	$c^3 - 1$	$bc^2 - 6$	
				$bde - 1$			
				$c^2e - 3$			
				$cd^2 + 2$			

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I, x^{20}	J, x^{12}	K, x^{8}	L, x^{10}	M, x^{3}	N, x^{4}	O, x^{5}
$aceg$ +1	a^3f^2 +1	a^2dg +1	a^3ef +1	a^2cg^3 +1	a^2efg −1	a^2edg 0
cf^4 −1	$abef$ −10	ef −1	de −1	dfg −6	deg +1	cef −1
d^2g −1	cdf +4	$abeg$ −3	ab^2f −1	c^2g +8	df^2 +3	d^2f +3
def +2	ce^3 +16	bdf −2	bce −2	ef^2 −3	e^2f −3	de^2 −2
e^3 −1	d^2e −12	be^2 +5	bd^2 +4	ab^2g^2 −1	ab^2fg +1	ab^2dg 0
a^2b^2eg −1	a^2b^2df +16	c^2f +9	c^2d −1	$bcfg$ +6	$bceg$ +2	b^2ef +1
b^2f^3 +1	b^2e^2 +9	cde −17	a^2b^2e +3	$bdeg$ −34	bcf^2 −3	bc^2g 0
$bcdg$ +2	bc^2f −12	d^3 +8	b^2cd −6	bdf^2 +48	bd^2g −4	$bcdf$ −14
$bcef$ −2	$bcde$ −76	a^2b^2g +2	bc^3 +3	bc^2f −18	$bdef$ −12	bce^2 +11
bd^2f −2	bd^3 +48	b^2cf −6		c^2eg +18	be^3 +15	bd^2e +1
bde^2 +2	c^2e +48	b^2de +2		c^2f^2 −45	c^2dg +1	c^2f +9
c^2g −1	c^2d^2 −32	bc^2e +6		cd^2g +4	c^2ef +9	c^2de −14
c^2df +2		bcd^2 −4		$cdef$ +78	cf^2 +4	cd^3 +6
c^2e^2 +1				ce^3 −36	cde^2 −21	a^2b^2eg 0
cde −3				df^2 −48	d^2e +8	b^2df +8
d^4 +1				d^2e^2 +28	a^2b^2eg −3	b^2e^2 −9
				a^2b^2ceg 0	b^2cdg +6	b^2c^2f −6
				b^2c^2g +64	b^2cef +9	b^2cde +16
				b^2def −144	b^2c^2f +32	b^2d^2 −8
				b^2e^3 +81	b^2de^2 −39	bc^2e −3
				bc^2dg −96	bc^2g −3	bc^2d^2 +2
				bc^2ef +108	bc^2df −66	
				bcd^2f +96	bc^2e^2 +18	
				$bcde^2$ −126	bcd^2e +76	
				bd^2e +16	bd^4 −32	
				c^4g +36	c^4f +27	
				c^3df −72	c^3de −45	
				c^3e^2 −27	c^3d^2 +20	
				c^2d^2e +96		
				cd^4 −32		

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P, α^6	
$a^4d^2g^3$	+ 1
$def g$	— 6
df^3	+ 4
e^3g	+ 4
e^2f^3	— 3
$abcdg^3$	— 6
$bcefg$	+ 18
bef^3	— 12
bd^2fg	+ 12
bde^2g	— 18
be^2f	+ 6
c^2g^3	+ 4
c^2e^2g	— 24
c^2dfg	— 18
c^2ef^3	+ 30
cd^2eg	+ 54
cd^2f^3	— 12
cde^2f	— 42
ce^4	+ 12
d^4g	— 20
d^2ef	+ 24
d^2e^3	— 8
$a^2b^2dg^3$	+ 4
b^2efg	— 12
b^2f^3	+ 8
$b^2c^2g^3$	— 3
b^2ce^2g	+ 30
b^2cef^3	— 24
b^2d^2eg	— 12
$b^2d^2f^3$	— 24
b^2de^2f	+ 60
b^2e^4	— 27
bc^2fg	+ 6
bc^2deg	— 42
bc^2df^3	+ 60
bc^2e^2f	— 30
bcd^2g	+ 24
bcd^2ef	— 84
$bcde^3$	+ 66
bd^3f	+ 24
bd^2e^3	— 24
c^4eg	+ 12
c^4f^3	— 27
c^3d^2g	— 8
c^3def	+ 66
c^3e^3	— 8
c^2d^2ef	— 24
$c^2d^2e^3$	— 39
cd^3e	+ 36
d^6	— 8

Q, x^4		R, x^6	
a^3dg^3		—	1
efg		+	9
f^3		—	8
a^3bcg^3		+	3
$bdfg$		—	24
be^2g		—	45
bef^3		+	66
c^2fg	— 2	+	3
$cdeg$	+ 5	+	48
cdf^3	+ 6	—	12
ce^2f	— 7	—	51
d^2g	— 3	—	16
d^2ef	— 3	+	36
de^3	+ 4	—	8
ab^2g^3	0	—	2
b^2efg	+ 4	+	12
b^2deg	— 5	+	102
b^2df^3	— 6	—	48
b^2e^2f	+ 7	—	144
bc^2eg	— 5	—	159
bc^2f^3	— 6	+	18
bcd^2g	+ 7	—	48
$bcdef$	+ 16	+	24
bce^3	+ 23	+	279
bd^2f	+ 30	—	48
bd^2e^3	— 33	—	84
c^3dg	— 1	+	42
c^3ef	+ 36	+	153
c^2d^2f	— 37	—	36
c^2de^3	— 53	—	399
cd^2e	+ 79	+	312
d^5	— 24	—	64
a^2b^2fg	— 2		0
b^2ceg	+ 5		0
b^2cf^3	+ 6		0
b^2d^2g	+ 2	—	224
b^2def	+ 22	+	144
b^2e^3	— 27	+	54
bc^2dg	— 8	+	336
bc^2ef	— 39	—	108
bcd^2f	— 50	+	384
$bcde^2$	+ 107	—	684
bd^2e	— 22	+	144
bc^3g	+ 3	—	126
bc^2df	+ 84	—	648
bc^2e^3	— 21	+	432
bc^2d^2e	— 102	+	564
bcd^4	+ 44	—	288
c^5f	— 27	+	270
c^4de	+ 45	—	450
c^3d^3	— 20	+	200

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Remaining Coefficients of C, E, G.

C	
x^2y	
af	$+ 2$
be	$- 6$
cd	$+ 4$
x^2y^2	
ag	$+ 1$
ce	$- 9$
d^2	$+ 8$
xy^3	
bg	$+ 2$
cf	$- 6$
de	$+ 4$
y^4	
eg	$+ 1$
df	$- 4$
e^2	$+ 3$

E	
xy	
adg	$+ 1$
aef	$- 1$
beg	$- 1$
bdf	$- 8$
be^2	$+ 9$
c^2f	$+ 9$
cde	$- 17$
d^3	$+ 8$
y^3	
aeg	$+ 1$
af^2	$- 1$
bdg	$- 3$
bef	$+ 3$
c^2g	$+ 2$
cdf	$- 1$
ce^2	$- 3$
d^2e	$+ 2$

G	
x^3y	
a^2g	$+ 1$
abf	$+ 2$
ace	$- 19$
ad^2	$+ 8$
b^2e	$- 6$
bcd	$+ 44$
c^3	$- 30$
x^2y^2	
abg	$+ 7$
acf	$- 14$
ade	$- 14$
b^2f	0
bce	$- 21$
bd^2	$+ 112$
c^2d	$- 70$
x^3y^3	
aeg	$+ 7$
adf	$- 28$
ae^2	$- 14$
b^2g	$+ 14$
bef	$- 42$
bde	$+ 168$
c^2e	$- 105$
x^4y^4	
adg	0
aef	$- 35$
beg	$+ 35$
bdf	0
be^2	$+ 105$
c^2f	$- 105$

G	
x^3y^3	
aeg	$- 7$
af^2	$- 14$
bdg	$+ 28$
bef	$+ 42$
c^2g	$+ 14$
cdf	$- 168$
ce^2	$+ 105$
x^2y^4	
afg	$- 7$
beg	$+ 14$
bf^2	0
cdg	$+ 14$
cef	$+ 21$
d^2f	$- 112$
de^2	$+ 70$
xy^7	
ag^2	$- 1$
bfg	$- 2$
ceg	$+ 19$
cf^2	$+ 6$
d^2g	$- 8$
def	$- 44$
e^3	$+ 30$
y^8	
bg^2	$- 1$
cfg	$+ 5$
deg	$- 2$
df^2	$- 8$
e^2f	$+ 6$

Note.—In the tables on this page, a has been treated like the other letters; on the preceding pages, the powers of a have been suppressed except in the first of every series of terms containing a common power of a.

The final result is that we have the values of the invariants B, I, P, W, Z and the leading coefficients of the covariants A, C, D, E, F, G, H, J, K, L, M, N, O, Q, R: also the means of calculating the leading coefficients of the remaining covariants S, T, U, V, X, Y.

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